Volume 29 DECEMBER, 1959 Number 4

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TEXTURE AND COMPOSITION OF SOME WEATHERED GRANITES AND SLIGHTLY TRANSPORTED ARKOSIC SANDS[1]

MICHAEL C. McEWEN, FRANKLIN W. FESSENDEN, AND JOHN J. W. ROGERS
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ABSTRACT

Samples of thoroughly disintegrated granite from a granitic knob (Sandstone Mountain) in the Llano area of central Texas and from Flagstaff Mountain, Colorado, exhibit bulk sample size distributions which follow Rosin's law of crushing. This same distribution is also found in samples which have traveled several hundred yards down a small intermittent stream draining Sandstone Mountain. Less completely disintegrated granite samples from Bear Mountain, Texas, and Flagstaff Mountain depart from Rosin's law in showing a deficiency in the finer sizes. Hornblende grains weathered out of the granite at Sandstone Mountain without fracturing and zircon grains in weathered granite at Flagstaff Mountain exhibit the lognormal distribution which they probably had in the fresh granites.

Mineralogy and grain size are closely correlatable in the disintegrated granites from Texas. The percentage of quartz and rock fragments increases with increasing grain size whereas the percentage of the feldspars and heavy minerals decreases. The tendency of quartz and rock fragments to be more spherical than feldspar causes sphericity to increase with grain size. The decrease of sphericity with decreasing grain size is shown both in the samples from the Llano area and from Flagstaff Mountain.

INTRODUCTION

An understanding of the properties of non-transported sedimentary debris is essential in interpreting the history of transportation and deposition of clastic sediments. The present study, therefore, was conducted for the purpose of describing mineralogically and texturally some typical weathering products of granitic rocks. Materials studied include weathered grus on two granitic knobs (Bear Mountain and Sandstone Mountain) in the Llano area of central Texas, samples from a small intermittent stream draining one of the knobs, and samples from weathering profiles and nearby arkose on a granite outcrop on Flagstaff Mountain, near Boulder, Colorado. The information obtained concerns the size distribution, shape, roundness, and mineralogic composition of the sedimentary material. Chemical features of the weathering at Flagstaff Mountain have previously been extensively described by Wahlstrom (1948). Size distributions of various source rocks of sediments have been discussed by Krumbein and Tisdel (1940).

PETROGRAPHY OF THE GRANITES

The two granites at Bear Mountain and Sandstone Mountain, Texas, are compositionally, though not texturally, similar. Petrographic examination shows that the granite studied at Bear Mountain consists of roughly equal amounts of quartz, plagioclase, and microcline. The plagioclase is subhedral to anhedral, the quartz occurs in aggregates of undulant grains, and the microcline is largely interstitial. The rock is equigranular and has an estimated average grain size of 1.5 mm. The granite at Sandstone Mountain consists of approximately equal amounts of quartz, plagioclase, and microcline with minor biotite and hornblende. It is equigranular and fine grained (average grain size of 0.5 mm); all grains are anhedral. The granite at Sandstone Mountain is characterized by abundant quartz blebs in both microcline and plagioclase, some of which resemble graphic and myrmekitic textures. The granites have been studied more completely by Barnes, Dawson, and Parkinson (1942).

The granite on Flagstaff Mountain, Colorado, contains approximately equal amounts of quartz, potassium feldspar, and plagioclase with minor biotite and hornblende and rare accessory minerals. The rock is medium grained (average grain size of 2 mm) and porphyritic. All minerals are generally anhedral. The quartz forms aggregates of undulant, sutured grains, but the biotite and accessory minerals are uni-

[1] Manuscript received May 28, 1959.

formly scattered. Myrmekite is abundant on the borders of plagioclase grains, and the plagioclase is slightly sericitized. Additional information is given by Wahlstrom (1948).

PROCEDURE

Weathered material from the granites from the Llano area and from Flagstaff Mountain differed with respect to amount of clays and micas (higher at Flagstaff Mountain), the amount of clayey alteration of mineral grains (higher at Flagstaff Mountain), and the amount of organic material (higher in most of the samples from the Llano area). Consequently, slightly different procedures had to be adopted in preparing and analyzing the samples from the two areas; the methods used in each case are described below. The samples from the Llano area were studied first.

Llano Area

Three samples of non-transported grus were collected from exfoliation pockets in Bear Mountain, north of Fredericksburg, Gillespie County, Texas. Three other samples were collected from exfoliation pockets in a small hill just north of Sandstone Mountain, southeast of Llano, Llano County, Texas; hereafter, for convenience, this hill is referred to as Sandstone Mountain. In order to minimize the effect of addition or removal of material, only pockets near the tops of the mountains which have no inlet or outlet channels were sampled. Obviously, material has been removed from the granite in order to form the exfoliation pocket, but the debris in the pocket at any one time probably represents material which has recently disintegrated and has been only slightly disturbed. For each sample enough material was taken to fill a six-inch cloth bag.

Eight samples were taken from an intermittent stream which drains to the north of Sandstone Mountain. The stream, nowhere wider than 5 ft nor deeper than 1 ft, empties into the Llano River at a distance of about one half mile from the hill and drops about 125 ft in that half mile. The average distance between sampling locations was about 100 yards. In all tables in this paper, samples are listed in order of increasing distance from the hill.

Most of the samples were treated with either a 15 percent or a 30 percent solution of hydrogen peroxide for the removal of organic material. All samples were then boiled in dilute hydrochloric acid with stannous chloride to remove iron stain. The samples were washed with water using Pasteur-Chamberland filters (Krumbein and Pettijohn, 1938, p. 67) connected to a vacuum. If, upon drying, the grains formed aggregates, the sample was gently rolled with a rubber pestle. Each sample was then split, using a Jones sample splitter, to an amount suitable for sieving.

The clays in the Bear Mountain grus samples (43b, 44b, and 45b) formed a cake on the larger grains. This cake was removed by soaking the sediment overnight in a solution of Calgon to disperse the clays, stirring, and washing the samples on a U. S. 325 mesh (44 micron) sieve. The material retained on the screen was dried and weighed and the amount passing through the screen determined by difference.

All samples were run through a series of six sieves chosen from a $\sqrt[4]{2}$ scale. The six sieves and pan were placed in a Tyler Ro-Tap for 10 minutes. In samples 44b and 45b grains larger than 1 cm were measured with a ruler.

Roundness and sphericity of each size grade were estimated visually using a binocular microscope. Roundness values were determined by comparison, using the Powers (1953) visual scale. Sphericity was estimated visually by comparison with the chart in Krumbein and Sloss (1951, p. 81).

The mineralogic composition of the six grus samples and three of the stream samples was determined by oil immersion methods for each size grade less than 20 mesh (840 microns). Using a petrographic microscope, 300 grains were counted from a representative portion of each size grade mounted in immersion oil of index 1.532. Grains larger than 840 microns cannot be studied conveniently by this method. All bi- or polymineralic grains were classified as rock fragments.

The smaller size grades of the bulk samples were combined and split with an Otto Microsplit to approximately 7 to 10 gm, and heavy minerals were separated from these aggregate samples. The maximum size grade combined depended on the relative amount of material in the larger sizes; if the

bulk of one of the coarser fractions (40 or 60 mesh) greatly outweighed the combined bulk of the smaller size grades, the coarser size grade was not included with the combined lower sizes. In no case was material coarser than that retained on the 40 mesh sieve used. After passing through the microsplit, the sample was centrifuged in bromoform for 10 minutes at approximately 2500 rpm. It was then stirred and re-centrifuged twice. The bromoform in the lower part of the tube was then frozen and the light minerals in the upper part poured off. A representative portion of the heavy minerals of each sample was mounted in canada balsam.

The size distribution of hornblende grains was measured in four samples by means of a petrographic microscope with a calibrated ocular. The long dimension of 300 grains was measured in three samples, but in sample 54 only 256 grains were encountered in traversing the slide.

Flagstaff Mountain

Twelve samples were collected from the weathered granite at Flagstaff Mountain, and one sample (FF 2) was taken from Fountain Arkose (Pennsylvanian) at the contact with the granite. Of the weathered samples, 10 are from the pre-Fountain weathering profile (described by Wahlstrom, 1948). Samples FM 1–8 are from the 30-foot thick red zone, with increasing numbers indicating greater depth below the Fountain contact. Samples FM 9 and 10 are from the 50-foot thick bleached zone between the red zone and the fresh granite. Sample FM 11 is from the surface of the outcrop and represents recent weathering. Sample FM 12 is from a point further down in the recent weathering profile.

All samples were disaggregated by soaking in Calgon for several days and then stirring gently with a glass rod. Samples were then boiled in a solution of stannous chloride in hydrochloric acid to remove iron stain.

The large proportion of clay made it necessary to remove most of the fine material (less than $\frac{1}{32}$ mm size) prior to sieving. For this purpose the entire sediment from the acid washing was poured into a beaker of water and allowed to stand sufficiently long (about 2 minutes) for all material of a size greater than $\frac{1}{32}$ mm to settle from the top of the beaker to the sediment on the bottom. The water and contained fines were then siphoned off and filtered. The recovered fine material was then weighed and used as an estimate of the $-\frac{1}{32}$ material in plotting the size distributions. It is interesting that, in most cases, the points plotted from these data fall rather closely on lines extrapolated on the size distribution graphs from the sieving data for the coarse material.

The above procedure for removing and estimating the fine fraction is complicated by the abundance of bleached mica in some of the samples because relatively coarse flakes of mica settled extremely slowly. The abundance of mica was so high in samples FM 11–12 and FF 2 that the clay and mica siphoned off were recovered on Pasteur-Chamberland filters, dried, and separated by sieving through a 170-mesh sieve. The mica was retained on the sieve and added to the coarse fraction for further sieving.

Samples were run through a series of 11 sieves chosen from a $\sqrt[4]{2}$ scale. The relatively large number of sieves was used in order to detect the expected very minor variations in size distribution with depth in the weathering profile. Samples were sieved in two stages for 10 minutes each in a Ro-Tap shaker.

Roundness and sphericity of alternate size grades were estimated visually using a binocular microscope. Roundness comparisons were made with the Powers (1953) scale; sphericity was estimated by comparison with the chart in Krumbein and Sloss (1951, p. 81).

Heavy minerals were separated from each sample by centrifuging a representative part of the -20 mesh portion of each sample in bromoform. Size distributions of zircon grains were determined by measuring the long dimensions of 300 grains of the -80 mesh fraction in balsam mounts.

Many of the grains, especially the feldspars, were highly altered by chemical weathering; consequently, no accurate information was obtained on the variation of mineralogical composition with grain size.

RESULTS AND DISCUSSION: LLANO AREA

Roundness

Grains less than 0.25 mm in samples 54 and 57 are "angular"; all other size grades of all samples average "very angular" in the classification of Powers (1953). Thus, there

TABLE 1.—*Estimated average sphericity of different size grades of samples from the Llano area*

	U. S. Mesh	4	12	20	40	60	100	120	140	230	325
	Millimeters	4.760	1.680	.840	.420	.250	.149	.125	.105	.062	.044
	43b		.80	.75	.80	.80		.70		.70	
	44b	.80	.80	.75	.75	.65		.65			.55
	45b	.80	.70	.70	.70	.70		.70			.60
	49			.80	.80	.75	.75	.65		.60	
	50			.85	.80	.80	.75	.75		.65	
	28			.70	.75	.75	.70		.65	.60	
Samples	51		.80	.80	.80	.80		.70		.60	
	52		.70	.80	.80	.75		.65		.60	
	53		.80	.80	.75	.75		.75		.60	
	33			.80	.80	.80	.70		.60	.60	
	54			.80	.80	.75	.75	.70		.60	
	55		.80	.75	.80	.75		.75		.50	
	56		.70	.80	.80	.80		.80		.70	
	57			.80	.80	.80	.70	.70		.50	

is no detected relationship between size and roundness of particles, though such a relationship may certainly exist. No difference in roundness between grains of the grus in place and grains of the stream sands is apparent.

A few anomalously sub-rounded and rounded quartz grains appear in the finer sizes of some of the samples. These grains may represent myrmekitic quartz released from fractured feldspar, for petrographic examination of the Sandstone Mountain granite shows it to contain an unusually large amount of myrmekite and rounded quartz blebs, which may be "end-on" views of myrmekitic intergrowths.

Sphericity

The results summarized in table 1 indicate a clear correlation between grain size and sphericity in that the larger grains are more spherical. This relationship of decreasing sphericity with decreasing size is equally true for non-transported grus and for stream sands. Consequently neither attrition nor sorting can account for the relationship, and it appears that the sphericity of a particular size grade is controlled largely by the relative percentage of feldspar, quartz, and rock fragments.

Grains of the largest size grades, which consist largely or entirely of rock fragments, are the most nearly spherical; thus the rock

TABLE 2.—*Mineralogic composition of grus samples from Bear Mountain*

Sample	U. S. Mesh	Millimeters	Quartz	Plagioclase	Potassium Feldspar	Biotite	Rock Fragments	Heavy Minerals
	40	.420	45%	41%		—	14%	—
	60	.250	54	24	15	2	3	1
43b	120	.125	52	33	10	5	—	tr.
	230	.062	66	14	17	2	—	tr.
	40	.420	52%	30%	8%	3%	8%	—
44b	60	.250	36	39	12	10	3	1
	120	.125	22	52	11	12	1	1
	40	.420	43%	25%	12%	2%	19%	—
45b	60	.250	45	32	12	10	—	1
	120	.125	28	40	16	14	—	2

TABLE 3.—*Mineralogic composition of grus samples from Sandstone Mountain*

Sample	U. S. Mesh	Millimeters	Quartz	Plagioclase	Potassium Feldspar	Biotite	Rock Fragments	Heavy Minerals
	40	.420	48%	7%	22%	—	23%	—
	60	.250	41	20	36	tr.	4	—
49	100	.149	17	38	41	2	1	—
	120	.125	15	36	41	7	—	1
	230	.062	13	38	37	11	—	1
	40	.420	51%	5%	22%	tr.	22%	—
	60	.250	34	18	38	—	9	—
50	100	.149	29	31	38	2	—	1
	120	.125	22	30	43	4	—	2
	230	.062	32	23	38	3	—	3
	40	.420	37%	5%	21%	—	37%	—
	60	.250	36	21	34	—	8	tr.
28	100	.149	24	32	42	—	2	—
	140	.105	14	38	46	—	—	1
	230	.062	17	39	44	—	—	tr.

fragments, at least the larger ones, have a fairly high sphericity. In contrast, comparison of sphericity values in table 1 with percent feldspar in tables 2 to 4 and figures 1 to 3 shows that, in general, high sphericity correlates with a low percentage of feldspar. This is especially noticeable in the 120 and 230 mesh material of samples 50 and 43b; in each of these the percentage of plagioclase is lower and the sphericity higher than in the same size grade in other samples. Quartz grains in the samples studied are apparently more spherical than the feldspar. This relationship is shown by the correlation between sphericity and percentage of quartz in both grus and stream sands and is matched by petrographic evidence that the quartz grains of the granites are more nearly equidimensional than the feldspar. The tendency of the feldspars to break along cleavage planes is probably a factor contributing to the low sphericity of the smaller size grades.

Mineralogic Composition

The mineralogic composition was determined for each size grade below 0.84 mm in all grus samples from exfoliation pockets and

TABLE 4.—*Mineralogic composition of three samples from small stream north of Sandstone Mountain*

Sample	U. S. Mesh	Millimeters	Quartz	Plagioclase	Potassium Feldspar	Biotite	Rock Fragments	Heavy Minerals
	40	.420	40%	12%	21%	—	27%	—
	60	.250	46	16	31	—	7	—
54	100	.149	32	29	38	—	1	—
	120	.125	21	35	42	—	1	1
	230	.062	14	44	39	—	tr.	3
	40	.420	37%	10%	22%	—	31%	—
	60	.250	43	20	33	—	3	1
55	120	.125	29	33	35	—	1	3
	230	.062	32	24	33	3	—	8
	40	.420	37%	9%	23%	—	32%	—
	60	.250	39	23	30	tr.	7	1
56	120	.125	37	21	36	3	—	2
	230	.062	36	23	31	2	—	9

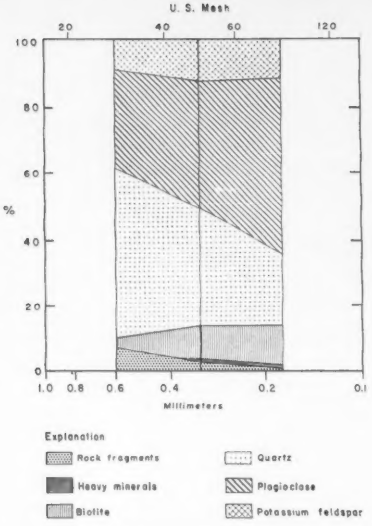

FIG. 1.—Mineralogic composition against grain size of Bear Mountain grus sample 44b.

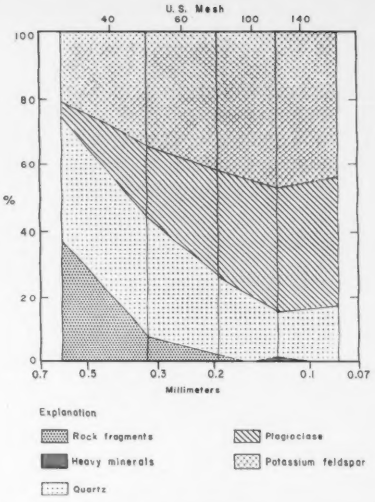

FIG. 2.—Mineralogic composition against grain size of Sandstone Mountain grus sample 28.

in three of the stream samples. Results are shown in tables 2 to 4 and figures 1 to 3. Most of the sediment consists of quartz, plagioclase, potassium feldspar, and rock fragments containing mostly these three minerals.

A definite correlation between grain size and mineralogy is apparent. The percentage of rock fragments increases markedly with increasing grain size. With one exception, sample 43b, the percentage of quartz increases with increasing grain size in the size range examined, although it must obviously decrease in the very coarse sizes which consist predominantly of rock fragments. In some of the samples the percentage of quartz shows a slight increase in the finest size grades, possibly owing to the release of myrmekitic quartz from fractured or weathered feldspar. The percentage of feldspars consistently increases with decreasing grain size down to about 0.1 mm. Heavy mineral content, though minor, shows a consistent increase with decreasing grain size. The most abundant heavy mineral is green hornblende; other heavy minerals include zircon, sphene or monazite, tourmaline, clinozoisite,

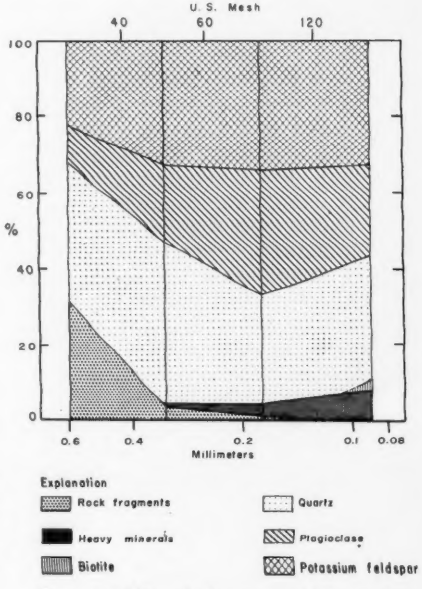

FIG. 3.—Mineralogic composition against grain size of sample 55, from small stream north of Sandstone Mountain.

magnetite, and rutile. Biotite is concentrated in the finer sizes.

The relative percentage of quartz and feldspar in the various size grades appears to be dependent upon two factors: (1) the size distribution of quartz and feldspar in the granite, since in thin sections of both granites quartz appears to be larger than the feldspars, and (2) in weathering, feldspars have a greater tendency to cleave into smaller particles than does quartz.

Size Distribution

Size distributions of bulk samples of grus and stream sands are discussed in the following section in terms of Rosin's law distributions. Rosin's law (Rosin and Rammler law) was originally formulated to describe the size distribution of crushed coal. Bennett (1936) gives a theoretical derivation of the law and a summary of experimental evidence. A special graph paper on which Rosin's law distributions plot as a straight line has been developed by Geer and Yancey (1938); sheets of this paper were obtained by the writers through the courtesy of the U. S. Bureau of Mines.

Based on the work of Krumbein and Tisdel (1940), it was expected at the start of the study that the grus samples would show a distribution very close to Rosin's law. This expectation is borne out by the samples from Sandstone Mountain. The Bear Mountain grus samples deviate somewhat from Rosin's law, however; the reasons for this deviation are discussed below. At the start of the work, the expected size distribution of the stream samples was uncertain. It seemed unlikely that transportation of a few hundred yards down stream could change markedly the distribution of the disintegrated source material, though differential removal of smaller grains could certainly have a pronounced effect. Many sediments, however, after prolonged transportation, exhibit a lognormal distribution, and it was considered possible that this distribution was imposed on the sedimentary debris by only a minor amount of stream transportation. The measured stream samples, however, approximate more closely a Rosin's law than a lognormal distribution.

Values of median size, sorting coefficient, and skewness for the measured size distributions of three grus samples (43b, 44b, and 45b) from exfoliation pockets in Bear Mountain are given in table 5. Samples 44b and 45b are from the same exfoliation pocket; 43b is from a different one. The size distributions of the three samples are shown graphically on Rosin's law paper (fig. 4) which indicates that the distribution deviates somewhat from Rosin's law. In samples 44b and 45b the departure from a Rosin's law distribution is the result of a deficiency of material of diameter less than 0.35 mm. This deficiency is probably partly offset by a small second mode in the silt or clay sizes, though the curve does not extend far enough into the finer sizes to show this mode. The basis for the presumed second mode is as follows: (1) the cumulative percent in the various size grades must total 100 percent, and (2) if the curves were extended toward the finer sizes at the same slope or the same rate of change of slope, a measurable percentage of the sample would be composed of colloidal or smaller sized particles. Consequently, it seems logical to hypothesize a second mode in the silt or clay sizes. It seems likely that these two modes represent two different products of weather-

TABLE 5.—*Median size, sorting coefficient, and skewness of bulk samples from the Llano area*

Sample	Median (in mm)	Sorting $\sqrt{Q_3/Q_1}$	Skewness Q_1Q_3/Md^2
43b	1.87	5.44	.13
44b	3.70	2.17	.90
45b	3.21	2.29	.92
49	0.360	1.88	.85
50	0.288	1.80	.85
28	0.545	1.66	.91
51	0.810	1.44	.98
52	0.538	1.53	.97
53	0.523	1.34	.99
33	0.502	1.47	.99
54	0.469	1.31	.96
55	0.870	1.55	.97
56	0.810	1.43	.95
57	0.374	1.47	.94

Samples 43b, 44b, and 45b are from grus at Bear Mountain. Samples 49, 50, and 28 are from grus at Sandstone Mountain. Samples 51–53, 33, and 54–57 are from stream north of Sandstone Mountain and are listed in order of increasing distance from the hill.

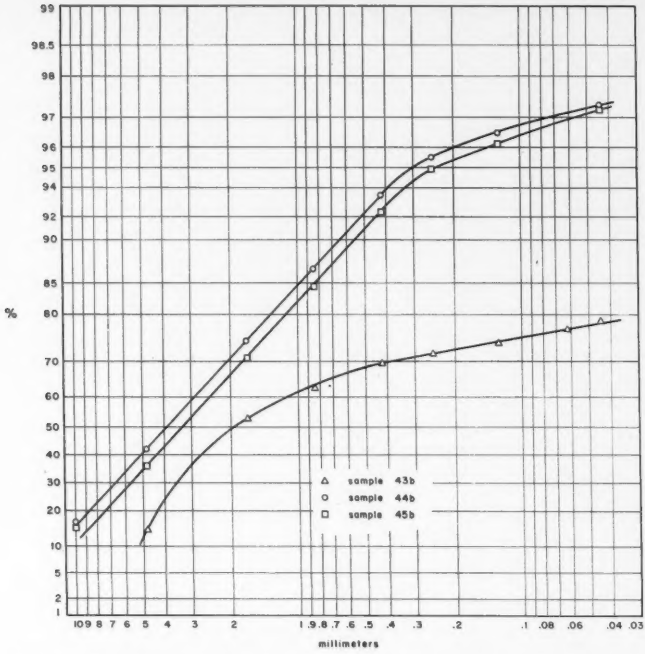

FIG. 4.—Size distributions of Bear Mountain grus samples. Rosin's law scale.

ing, the coarser material having formed by disintegration and the finer by decomposition. The disintegration products alone, however, do not follow the expected Rosin's law distribution, as can be readily shown by replotting the frequency distribution as if 100 percent of the sample were greater than clay size. Such a replotting indicates a true deficiency in the finer sizes of the disintegration product and leads to the conclusion that more complete disintegration of the Bear Mountain granite might produce a Rosin's law distribution. It is interesting to note that grus samples in different exfoliation pockets have different size distributions (as shown by comparing sample 43b with samples 44b and 45b). The reasons for this difference are unknown.

Samples of grus were collected from three different exfoliation pockets on Sandstone Mountain. Size distribution parameters are listed in table 5, and the distributions are shown graphically in figure 5. Apparently the grain sizes of these samples are distributed very closely in accordance with Rosin's law. The difference between the size distributions of the samples from Bear Mountain and Sandstone Mountain appears to be a function of the degree of disintegration of the granites. The average grain size of the Bear Mountain granite, as estimated from thin section, is about 1.5 mm; the average sizes of the Bear Mountain grus samples studied are 1.9, 3.2, and 3.7 mm. Conversely, the average grain size of the Sandstone Mountain granite in thin section is 0.5 mm, whereas the medians of the grus samples are 0.3, 0.4, and 0.5 mm. Although grain sizes estimated in thin section are obviously not comparable with sizes measured by sieving, nevertheless the relative grain sizes of granites and grus samples indicates that the granite at Sandstone Mountain is more disintegrated than that at Bear Moun-

tain. The close approach of the Sandstone Mountain grus samples to a Rosin's law distribution bears out the conclusion that complete disintegration produces such a size distribution.

Eight samples, numbers 51–53, 33, and 54–57, in that order, were taken from the source to the mouth of the small stream draining to the north of Sandstone Mountain. Size distribution parameters are shown in table 5, and distributions of three of the samples are illustrated in figure 6. These graphs show that the sediment follows a Rosin's law distribution, as does the grus from exfoliation pockets in Sandstone Mountain. The stream has not changed the nature of the distribution, although it has increased the median diameter and reduced the sorting coefficient of the sands relative to the original grus.

The size distributions of hornblende grains were measured in two grus samples from Sandstone Mountain and in two stream samples. Results are shown graphically on log-probability paper in figures 7 to 10, and various parameters are listed in table 6.

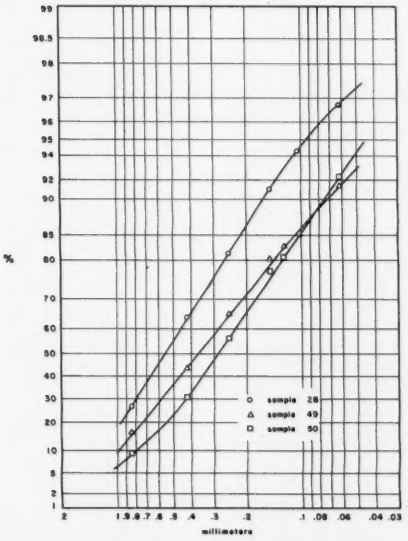

FIG. 5.—Size distributions of Sandstone Mountain grus samples. Rosin's law scale.

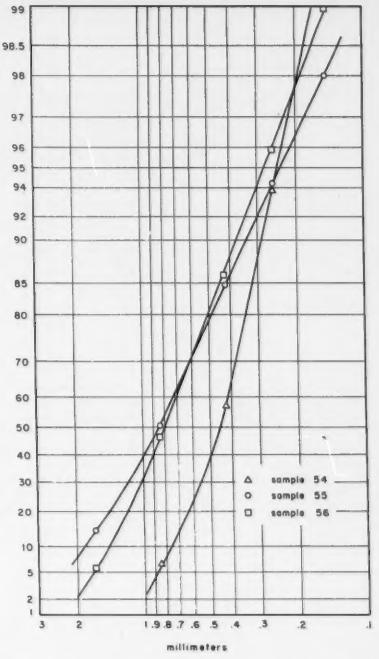

FIG. 6.—Size distributions of three samples from stream north of Sandstone Mountain. Rosin's law scale.

Median sizes of hornblende grains cannot be compared to median sizes of the bulk materials for the reason that the hornblende size distribution is based on number frequency of the long axes of the grains, whereas the bulk sample distribution is based on weight frequency measuring roughly the intermedi-

TABLE 6.—*Median size, sorting coefficient, and skewness of hornblende size distributions*

Sample	Median (in mm)	Sorting $\sqrt{Q_3/Q_1}$	Skewness Q_1Q_3/Md^2
49	.083	1.35	1.01
28	.083	1.33	1.03
54	.131	1.88	1.28
56	.190	1.60	1.03

Samples 49 and 28 are from grus at Sandstone Mountain. Samples 54 and 56 are from small stream north of Sandstone Mountain

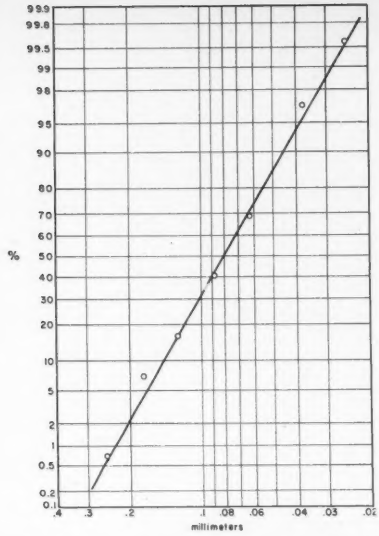

FIG. 7.—Size distribution of long dimensions of hornblende grains in sample 49, from grus at Sandstone Mountain. Log-probability scale.

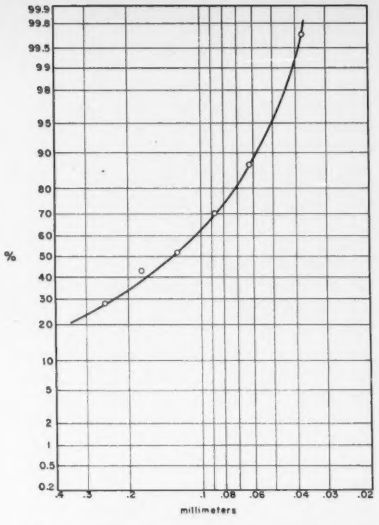

FIG. 9.—Size distribution of long dimensions of hornblende grains in sample 54 from stream north of Sandstone Mountain. Log-probability scale.

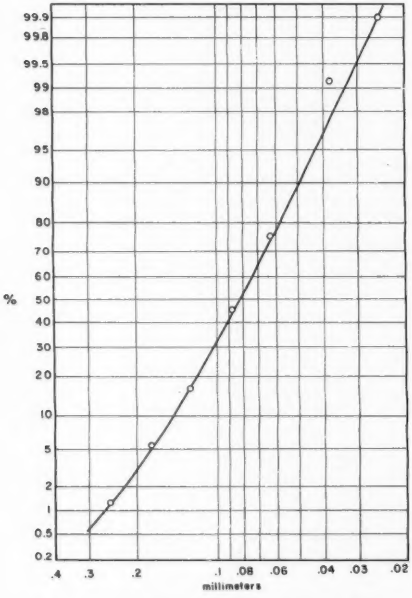

FIG. 8.—Size distribution of long dimensions of hornblende grains in sample 28, from grus at Sandstone Mountain. Log-probability scale.

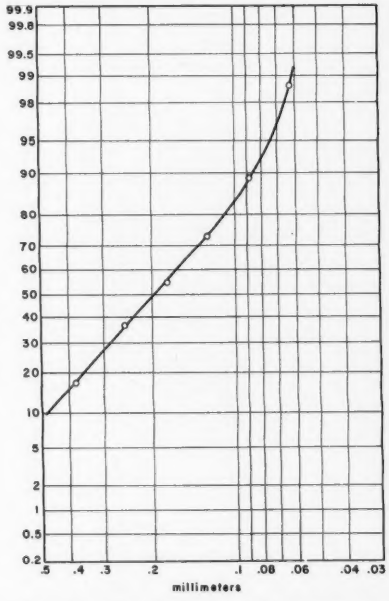

FIG. 10.—Size distribution of long dimensions of hornblende grains in sample 56 from stream north of Sandstone Mountain. Log-probability scale.

ate grain diameter. The size distribution of the hornblende grains in the grus samples is lognormal, possibly relict from the expected lognormal size distribution of the grains in the fresh rock (Rogers and Dawson, 1958). The lognormal distribution postulated for crystals forming in a homogeneous medium would probably apply to the early-crystallizing hornblende grains in the granite of Sandstone Mountain even though the abundant myrmekitic and graphic texture in the granite indicates that the later-forming minerals grew in a heterogeneous medium. If the lognormal distribution in the grus samples is really inherited from the fresh rock, then presumably the hornblende did not undergo appreciable fracturing during weathering. The size distribution of hornblende grains in the stream samples, however, departs significantly from the lognormal. Apparently the stream increased the median diameter and decreased the sorting coefficient by selectively removing the finer grains. The shape of the distribution curves for the stream samples indicates an excess (relative to lognormal) of hornblende in the finest sizes measured but rather clearly shows a deficiency in sizes smaller than the smallest measured sizes (about 0.05 mm).

RESULTS AND DISCUSSION: FLAGSTAFF MOUNTAIN

Roundness

All grains of major minerals (quartz and feldspars) in all size grades of each sample average "angular" in the roundness scale of Powers (1953); consequently data for individual samples are not tabulated. Feldspars in weathered samples from Flagstaff Mountain are more rounded than the very angular grains from disintegrated granites and stream sands in the Llano area. This greater roundness may be caused by more intense chemical weathering in the Flagstaff Mountain area.

Sphericity

Estimated average sphericities of various size grades from each sample are shown in table 7. As in the disintegrated granitic material from the Llano area, sphericity generally decreases slightly with decreasing grain size. This relationship is true both for the slightly transported sediment (sample FF 2) and for the samples of granite weathered in place. The reason for this relationship between sphericity and grain size could not be established definitely, although the variation may be caused by the variation of mineralogical composition with grain size, as in the case of the Llano samples.

Size Distribution

Median size, sorting coefficient, and skewness of all bulk samples from Flagstaff Mountain are given in table 8. Size distributions of samples from the red pre-Fountain weathering zone are shown in figures 11 and 12, from the bleached pre-Fountain weathering zone in figure 13, from the recent weathering zone in figure 14, and from Fountain Arkose at the contact with granite

TABLE 7.—*Estimated average sphericity of different size grades of samples from Flagstaff Mountain*

U. S. Mesh		12	20	60	120	170	230
Millimeters		1.680	.840	.250	.125	.088	.062
FM	1	.65	.60	.65	.60	.60	.65
	2	.70	.60	.60	.60	.60	.55
	3	.70	.70	.55	.50	.50	.60
	4	.80	.70	.65	.60	.60	.60
	5	.65	.60	.55	.60	.55	.60
	6	.65	.70	.60	.60	.60	.60
	7	.75	.60	.60	.60	.50	.60
	8	.65	.60	.60	.50	.50	.55
	9	.70	.70	.65	.60	.60	.60
	10	.70	.70	.70	.60	.50	.50
	11	.65	.50	.50	.50	.50	.50
	12	.60	.55	.50	.55	.55	.55
FF	2	.70	.70	.65	.60	.60	

TABLE 8.—*Median size, sorting coefficient, and skewness of bulk samples from Flagstaff Mountain*

Sample		Median (in mm)	Sorting $\sqrt{Q_3/Q_1}$	Skewness Q_1Q_3/Md^2
FM	1	.695	2.91	.67
	2	.765	2.20	.85
	3	.920	2.14	.79
	4	.640	2.56	.78
	5	1.20	2.86	.52
	6	1.10	2.88	.50
	7	1.45	2.33	.59
	8	2.45	1.91	.47
	9	1.55	3.04	.61
	10	.845	2.56	.69
	11	3.40	1.52	.76
	12	1.60	2.02	.77
FF	2	1.30	1.92	.73

Samples FM 1–8 are from the red pre-Fountain weathering zone and are listed in that order in increasing depth below the overlying contact. Samples FM 9–10 are from the bleached pre-Fountain weathering zone. Samples FM 11–12 are from the recent weathering zone. Sample FF 2 is Fountain arkose at the contact with weathered granite.

in figure 15. All size distributions are plotted on Rosin's law paper for reasons discussed in the description of samples from the Llano area.

The study of samples from the Llano area showed that more thoroughly disintegrated granite generally approached more closely to a Rosin's law distribution than granite which had disintegrated only slightly. Consequently, samples FM 1–10 were compared carefully to determine whether more completely weathered samples (with lower numbers, higher in the weathering profile) had size distributions closer to Rosin's law than the fresher samples. As shown by figures 11 to 13, samples FM 1–4 (highest in the profile) fit a Rosin's law distribution slightly better than samples FM 5–8, though the differences are very small. A second mode in the silt or clay fraction, hypothesized for the samples of grus at Bear Mountain, may also be present in samples FM 5–8 and FM 1. No such excess of fine material need be hypothesized, however, for samples FM 2–4. The silty or clayey material in the fine mode may be a decomposition product, in contrast to the coarser disaggregation products which comprise the major part of the

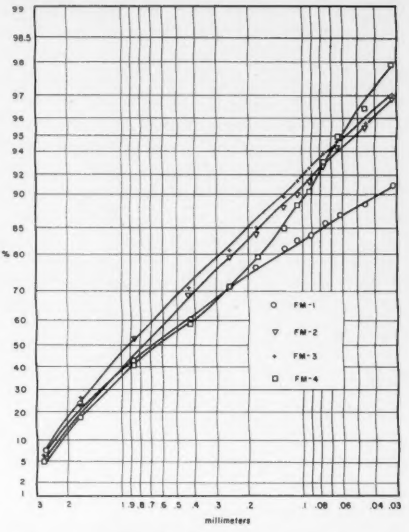

FIG. 11.—Size distributions of samples from the red pre-Fountain weathering zone at Flagstaff Mountain. Rosin's law scale.

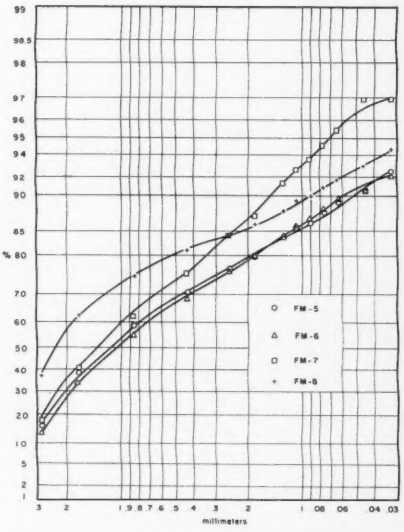

FIG. 12.—Size distributions of samples from the red pre-Fountain weathering zone at Flagstaff Mountain. Rosin's law scale.

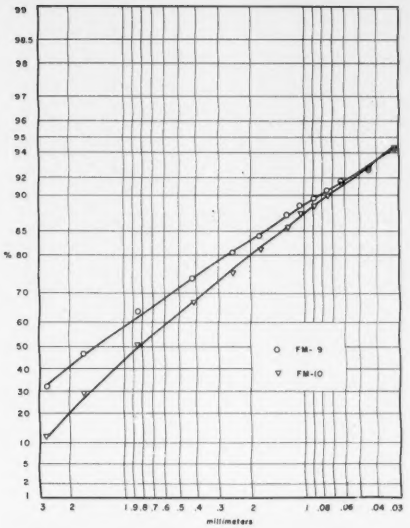

FIG. 13.—Size distributions of samples from the bleached pre-Fountain weathering zone at Flagstaff Mountain. Rosin's law scale.

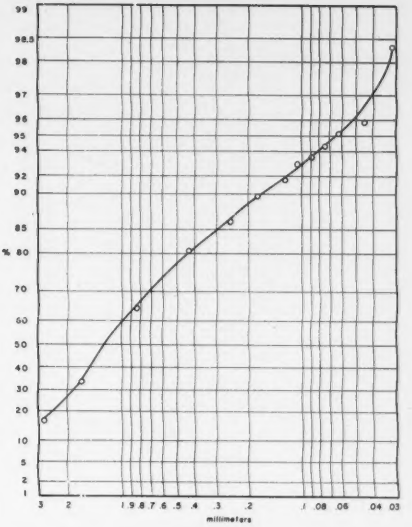

FIG. 15.—Size distribution of sample FF 2, Fountain Arkose at the contact with weathered granite. Rosin's law scale.

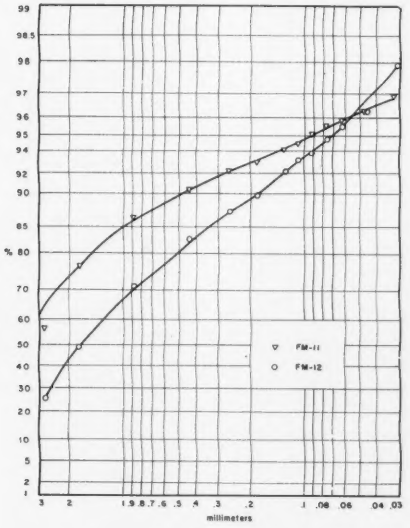

FIG. 14.—Size distributions of samples from the recent weathering zone at Flagstaff Mountain. Rosin's law scale.

distribution. Despite the possible second mode in the fine sizes, samples FM 5–8 deviate from Rosin's law distributions as a result of a general deficiency of material less than approximately 0.35 mm, the same size range deficient in the Bear Mountain samples. More continued disintegration, as in samples FM 2–4, removes this deficiency by breaking down the larger particles and results in a Rosin's law distribution.

On the basis of the above analysis it might be expected that samples FM 9–10, from the bleached zone between the red zone and the fresh granite, would also exhibit deficiencies in the range below 0.35 mm. These samples, however, approach a Rosin's law distribution as closely as the most weathered samples highest in the profile. The relationships between samples FM 9–10 and the overlying ones are not understood; it may be that the general deficiency of fine material in the lower part of the more weathered zone (samples FM 5–8) is caused by partial chemical solution rather than by incomplete disintegration, as proposed above, though both factors may be impor-

TABLE 9.—*Median size, sorting coefficient, and skewness of zircon samples from Flagstaff Mountain*

Sample	Median (in mm)	Sorting $\sqrt{Q_3/Q_1}$	Skewness Q_1Q_3/Md^2
FM 1	.102	1.35	.98
2	.078	1.28	1.00
3	.062	1.42	1.03
4	.078	1.40	1.00
5	.092	1.41	.99
6	.067	1.28	1.07
7	.079	1.37	1.03
8	.095	1.31	1.02
9	.085	1.31	1.01
10	.069	1.29	1.02
11	.085	1.31	1.01
12	.067	1.35	1.01

Samples FM 1–8 are from the red pre-Fountain weathering zone and are listed in that order in increasing depth below the overlying contact. Samples FM 9–10 are from the bleached pre-Fountain weathering zone. Samples FM 11–12 are from the recent weathering zone.

tant. A general increase in median size with decrease in weathering (depth in profile) is shown by the fact that samples FM 1–4 have the smallest, and FM 9–10 the largest median sizes in the weathering sequence.

The samples from the recent weathering profile (samples FM 11–12) show general deficiencies with respect to Rosin's law in the size range less than 0.35 mm (fig. 14). Whether or not this deficiency signifies incomplete disaggregation is uncertain.

Parameters of the size distributions of zircon grains in all samples from Flagstaff Mountain are listed in table 9, and several of the distributions are shown on log-probability paper in figures 16 to 19. The reasons for plotting the zircon size distributions on log-probability paper are discussed in the description of the size distribution of hornblende in the Llano samples. The zircon grains in the fresh granite are presumed to have a lognormal distribution similar to that of the hornblende grains in the Llano granites. Microscopic comparisons of the zircon grains in the weathered samples and in the

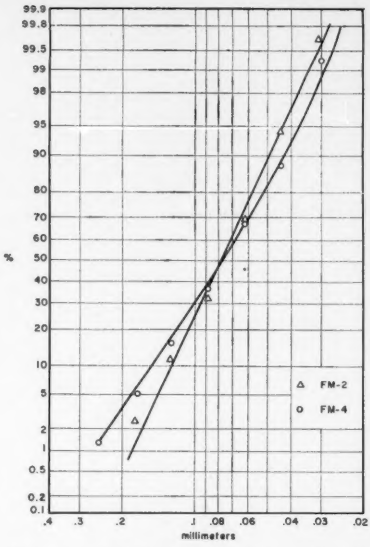

FIG. 16.—Size distributions of long dimensions of zircon grains in samples from the red pre-Fountain weathering zone at Flagstaff Mountain. Log-probability scale.

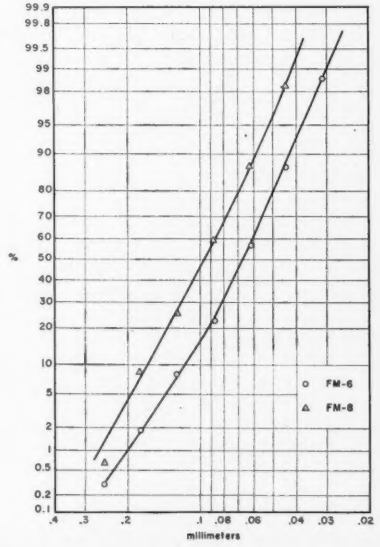

FIG. 17.—Size distributions of long dimensions of zircon grains in samples from the red pre-Fountain weathering zone at Flagstaff Mountain. Log-probability scale.

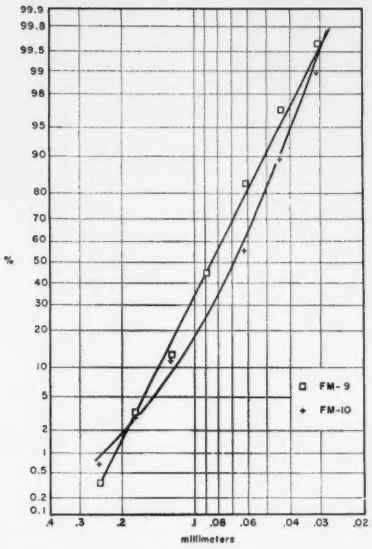

FIG. 18.—Size distributions of long dimensions of zircon grains in samples from the bleached pre-Fountain weathering zone at Flagstaff Mountain. Log-probability scale.

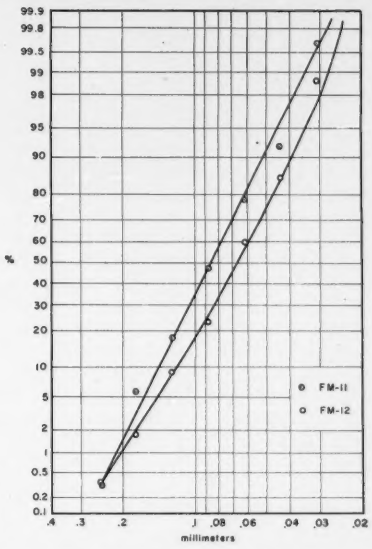

FIG. 19.—Size distributions of long dimensions of zircon grains in samples from the recent weathering zone at Flagstaff Mountain. Log-probability scale.

fresh granite show that the zircons have not been rounded or otherwise chemically attacked during weathering. Consequently, their roughly lognormal distribution, as shown by figures 16 to 19, is probably inherited from the original granite.

It is interesting that most of the zircon size distributions are positively skewed, whereas all of the bulk sample size distributions are negatively skewed. The same skewness relationship is seen in the samples from the Llano area, in which the hornblende size distributions are generally positively skewed, and the bulk sample size distributions negatively skewed. Minerals in the Flagstaff Mountain bulk samples (predominantly quartz and feldspars) have, of course, undergone extensive fracturing and chemical alteration, whereas the zircon grains have not been affected by weathering. The Llano grus samples, however, appear to have been affected chiefly by mechanical weathering. Thus the hornblende of these samples, just as the zircon of the Flagstaff Mountain samples, is not affected by weathering.

SUMMARY AND CONCLUSIONS

The size distribution of grus samples and weathered granitic rocks was found to approximate closely a Rosin's law distribution. Departures from Rosin's law are caused largely by incomplete disintegration of the granite upon weathering. Although stream processes change the median size and sorting of the sediment, the size distribution of stream sediments near their source also follows Rosin's law. From these results and the results of Krumbein and Tisdel (1940) it is concluded that, in general, the weathering of crystalline rocks tends to produce a size distribution corresponding to Rosin's law. Thoroughly disintegrated samples approach this distribution more closely than incompletely weathered material.

The size distribution of hornblende and zircon grains in the weathered material ap-

proaches lognormality. This distribution is expected because of the supposed lognormal size distribution of individual minerals in the fresh granite and negligible fracturing or chemical alteration of hornblende and zircon grains under the weathering conditions studied in the different areas. Slight transportation changes the shape of the distribution curve by selective removal of the finest sizes.

The cumulative effect of the various agents and processes acting on the sediment after its formation will, in general, impose a lognormal size distribution on the sediment. This lognormal distribution may be caused by abrasion and fracturing during prolonged transportation, by some property inherent in the hydraulics of stream flow, or by a random combination of processes and events (for example, see discussion by Kottler, 1950, p. 351) acting on the sediment during its transportation and deposition. Thus, further work may make it possible to attach some semi-quantitative significance to the Rosin's law distribution as an indicator of distance of transport, just as deviations from lognormality in more mature sediments may offer clues to their transportational and depositional history. Because of the almost unlimited number of combinations of factors which may produce a given size distribution in nature, it is unlikely that size distributions alone can be used as a sound basis for describing mode of transportation or environment of deposition; however, used in conjunction with other textural, environmental, and stratigraphic data, size distributions can be of substantial help in interpreting sediment history.

Roundness values in the samples studied show no detectable variation with grain size. Samples from Flagstaff Mountain, which have probably undergone more chemical weathering, are less angular than those from the Llano area. No rounding of grains by transport in the stream at Sandstone Mountain is apparent. Sphericity of grains decreases with decreasing grain size. In the Llano samples the variation is largely a result of variation in mineralogic composition; the correlation is caused primarily by an increase in quartz and rock fragment content and decrease in feldspar content with increasing size.

In disintegrated granites from the Llano area the percentage of quartz and rock fragments increases with increasing grain size whereas the percentage of feldspar and heavy minerals decreases. The variation of mineralogic composition with grain size is apparently a function of the grain size distribution in the granite and the tendency of feldspars to cleave as the granite disintegrates.

REFERENCES

Barnes, V. E., Dawson, R. F., and Parkinson, G. A., 1942, Building stones of central Texas: Univ. of Texas publication No. 4246. 198 p.

Bennett, J. G., 1936, Broken coal: Jour. Inst. Fuel, v. 10, p. 22–39.

Geer, M. R., and Yancey, H. F., 1938, Expression and interpretation of the size composition of coal: Am. Inst. Min. Met. Eng. Trans., v. 130, p. 250–269.

Kottler, F., 1950, The distribution of particle sizes: Franklin Inst. Jour., v. 250; part I, p. 339–356; part II, p. 419–441.

Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of Sedimentary Petrography. D. Appleton Century Co., Inc., New York, 549 p.

Krumbein, W. C., and Sloss, L. L., 1951, Stratigraphy and Sedimentation. W. H. Freeman and Co., Inc., San Francisco, 497 p.

Krumbein, W. C., and Tisdel, F. W., 1940, Size distribution of source rocks of sediments: Am. Jour. Sci., v. 238, p. 296–305.

Powers, M. C., 1953, A new roundness scale for sedimentary particles: Jour. Sedimentary Petrology, v. 23, p. 117–119.

Rogers, J. J. W., and Dawson, R. E., Jr., 1958, Size distribution of zircon and tourmaline grains in some samples of the Lissie Formation: Jour. Sedimentary Petrology, v. 28, p. 361–365.

Wahlstrom, E. E., 1948, Pre-Fountain and recent weathering on Flagstaff Mountain near Boulder, Colorado: Geol. Soc. America Bull., v. 59, p. 1173–1189.

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FIG. 1, DECEMBER, 1959

STABILITY OF INDEX MINERALS IN SOILS WITH PARTICULAR REFERENCE TO QUARTZ, ZIRCON, AND GARNET[1]

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ABSTRACT

In soil studies a group of index minerals has been generally accepted as sufficiently stable to be used as the basis for evaluating changes in soil profiles. Three of the minerals, quartz, garnet, and zircon, are shown to be susceptible to physical breakdown through strain caused by crystal disorientation or crystalline inclusions. Some varieties of garnet are susceptible to weathering, notably those with high iron content, and both quartz and zircon may be susceptible to solution. These minerals should, therefore, be used only in circumstances where physical or chemical changes can be excluded and where the minerals are free from crystalline inclusions and strain.

INTRODUCTION

Minerals that are resistant to weathering and physical breakdown are of particular interest to the pedologist, for the extent and the manner in which soil parent materials are altered during soil formation, and the movement of soil constituents either in solution or in colloidal form from one horizon to another, can most easily be determined by assuming that certain constituents remain unaltered throughout the history of the soil. In petrographic studies the minerals zircon, tourmaline, quartz, rutile, anatase, garnet, albite and microcline have been generally accepted as resistant to a greater or less extent, and these have, therefore, been proposed and used as reference minerals in studies on soil genesis.

Soil studies based on index minerals relate both to stratification of parent materials and to calculation of gains or losses of soil constituents during soil formation. Both kinds of study rest on the assumption that certain minerals remain unchanged during soil formation. The two studies are also complementary, for in computing gains or losses of soil constituents it is necessary to separate differences due to stratification from those produced by pedological processes.

On many sites it is a comparatively simple matter to detect stratification of parent materials by taking advantage of sharply contrasting mineral assemblages. Where these contrasts are wanting, however, the mineral distribution has to be studied in detail. In these circumstances careful consideration must be given to the stability of the minerals chosen.

Where gains or losses of soil constituents since the start of soil formation are being computed, the composition of the soil at the start of soil formation must be reconstructed. Where the soil rests on unweathered parent material this presents little difficulty, but where the soil is formed on deeply weathered parent material or parent material that was partly weathered before the start of soil formation, the stability of the index minerals is of prime importance.

Three criteria are generally used in soil studies that depend on the stability of the index minerals (Hasemann, 1944; Haseman and Marshall, 1945; Barshad, 1955):

(1) particle size distribution of certain resistant minerals,
(2) ratio of two resistant minerals in one particular size fraction,
(3) particle size distribution in the whole non-clay fraction of the soil.

The assumption that any particular index mineral is stable must embrace stability with respect to solution and chemical weathering, and also, because the criteria are based on particle size distribution of the minerals, with respect to physical breakdown of the mineral grains as well. It is not sufficient to assume that the minerals remain unchanged only during the formation of the main profile characteristics of the

[1] Soil Bureau Publication No. 186. Manuscript received July 15, 1959.

soil. The principal profile characters may be acquired early in the history of the soil and the profile may remain almost unchanged for long periods; but the index minerals may be subject to both chemical and physical change during this period of pedogenic inertia.[2]

To a large extent the order of stability of resistant minerals has been determined by statistical data based on their order of persistence in sediments, as, for example, the orders of stability proposed by Goldich (1938) and Pettijohn (1941). But it is by no means certain that a mineral that will remain inert and unaltered in a sediment will be equally so in a soil. Soils are subject, particularly in their upper horizons, to diurnal and seasonal temperature variations, and to prolonged leaching by percolating water, as well as to weathering of greater or less intensity according to the local environment. Moreover, changes in particle size distribution without any appreciable weathering (in a chemical sense) are of much greater significance to the pedologist than to the sedimentary petrographer. The soil is, in fact, a highly destructive environment, and for a mineral to be accepted as stable for all the soil studies enumerated it must be shown that under the local conditions it is resistant to:

(a) physical breakdown through splitting along cleavage planes or disruption from any other reason,
(b) authigenic outgrowths,
(c) weathering either through solution in the case of oxide minerals, or breakdown to secondary minerals in the case of silicate minerals.

Minerals that are subject to physical breakdown, although their total mass in the soil may remain unchanged, cannot be used in studies that assume constant particle size distribution. Minerals that are subject to weathering have neither a constant mass not constant particle size distribution.

Various minerals have been proposed as index minerals, the most comprehensive list being that of Barshad (1955) who lists zircon, tourmaline, quartz, rutile, anatase, garnet, albite, and microcline. Marshall (1940) had earlier proposed zircon, tourmaline, garnet, anatase, and rutile, and Adams and Matelski (1955) used zircon and tourmaline only. References in petrological literature to the stability of the individual minerals are few in number and for some of the minerals contradictory. The most valuable study is that of Carroll (1953) on the weatherability of zircon.

[2] This term is used in the sense proposed by Bryan and Teakle (1949).

QUARTZ

Quartz is widely distributed in soils of temperate regions as either a dominant or subdominant mineral. In the extensive area of soils derived from loess in the South Island of New Zealand it is co-dominant with feldspar. It is therefore an important and convenient index mineral. Pedological literature contains numerous references to quartz, the consensus of opinion being that it is resistant to weathering. A few writers, however, admit its stability with reservations.

Polynov (1937) states that "Primary quartz is such a stable substance and undergoes so little alteration that it may be considered to be quite passive in the zone of weathering which it leaves in the same form as that in which it entered." Russell (1950) accepts this view and rates quartz as "by far the commonest mineral in most soils and also the most resistant to decomposition." Barshad (1955) claims that th resistant minerals, in which he include quartz and albite, did not undergo significant change during the course of soil formation and that their particle size distribution pattern would remain unchanged.

Joffe (1949) also accepted quartz as one of the final residual products of weathering and held that it could not, under natural conditions of temperature and pressure, undergo further chemical changes, but he noted, nevertheless, that in soils it might be subject to solution and that alkali carbonates and alkali soluble complexes attacked it readily, citing a reference of Glinka's to some studies of Karpinksi on the Hebrew-stone soils of Murzinki from which quartz was leached and felspars remained intact. Joffe's attitude to the stability of quartz is thus somewhat contradictory. His further claim that "Conclusive evidence of the solubility of quartz is its presence in river wa-

ters" is not tenable. Silica is transported in river waters not as quartz but as monosilicic acid in true solution or as amorphous silica in colloidal form (Krauskopf, 1956), and the consensus of opinion is that most of it is derived from the decomposition of the silicate minerals or from other forms of silica such as opal.

The importance of the time factor in the solution of quartz has been recognised by Merrill (1897) who pointed out that if quartz is soluble, even to the extent of one part in ten thousand, the determining factor in the loss of quartz in solution is the amount of water that passes through the soil. Blanck (1949) also noted that although quartz may be only slightly soluble in water containing dissolved carbon dixodie, i.e., soil water, the process may be of long duration, and given sufficient time it can effect appreciable solution of quartz. Blanck also drew attention to the fact that quartz tended to split into sharp angular fragments, implying that this offset its low solubility.

Physical Stability

The following discussion of the physical stability of quartz refers to "pure" quartz or quartz with a negligible content of impurities such as aluminium and sodium. As the content of these impurities increases the stability of quartz would be expected to decrease.

Quartz possesses no well defined cleavage[3] along which splitting can take place easily, and quartz grains do not break down into cleavage flakes or rods in the same way as the amphiboles, for example. Quartz is, however, susceptible to strain effects which show up distinctly on the microscope stage under crossed nicols as undulose extinction, strain shadows, or irregular and uneven extinction. Strain is expressed in effect as a local dislocation of the crystal lattice and this in turn leads to stresses during thermal expansion. In accordance with its trigonal crystal symmetry, quartz possesses two principal coefficients of expansion, one parallel to the optic axis and the other normal to it. In the case of quartz, both coefficients of thermal expansion (α) are positive, that parallel to the optic axis being 8[4] and that normal to the axis 13 at room temperature. Thermal expansion is therefore likely to cause disruption at the site of local strain. Examination of quartz grains in soils shows that such disruption does, in fact, take place, incipient and well defined fracturing being associated with local strain.

Disruption from thermal expansion may also take place for another reason. Coarse quartz in metamorphic rocks is predominantly vein quartz. Vein quartz is particularly plentiful in the greywackes and schists of the South Island of New Zealand (Turner, 1942). It is made up of aggregates of quartz units with variously oriented optic axes, a thin section showing, under crossed nicols, a mosaic or patchwork of individual units in various stages of extinction. The texture of granulation in vein quartz is generally fine, and may range from fine sand to silt size. Thermal expansion of such an aggregate sets up stresses that may be expected to lead eventually to disruption and separation of the individual components of the mosaic, the surfaces of weakness lying at the contact of the individual grains of the mosaic. These effects may be intensified where the vein quartz also shows strain effects.

Rupture of quartz has been attributed to pressure exerted by inclusions, both gaseous and solid (Iddings, 1906). Recent work (Ingerson, 1955) has shown that appreciable pressure is not exerted by gaseous inclusions at normal pressures, and these cannot therefore be accepted as disruptive agents. Crystalline inclusions, however, would be expected to cause strain if the coefficient of expansion of the crystalline inclusion was less than that of the containing mineral where the containing mineral was formed at temperatures appreciably higher than normal. The coefficient of quartz perpendicular to the z axis is greater than the coefficients of the most common inclusions (see table 1). In quartz of soils in the South Island of New Zealand, crystalline inclusions are mostly confined to primary quartz and are less abundant in vein quartz.

[3] Quartz possesses a difficult cleavage parallel to $10\bar{1}1$ and $01\bar{1}1$ and in traces parallel to $10\bar{1}0$ and 0001, but these may be neglected for the purpose of this discussion.

[4] See table 1 for note on coefficient of expansion units.

TABLE 1.—*Coefficients of expansion of minerals occurring as inclusions (Clarke, 1927)*

	Coefficient of expansion αt°[1]		
Almandite (t=40°C)	8.37		
Magnetite (t=40°C	8.46		
	∥ to z axis	⊥ to z axis	
Anatase (t=40°C)	8.19	4.68	
Hematite (t=40°C)	7.61	7.71	
Quartz (t=40°C)	8.0	13.0	
Rutile (t=40°C)	9.19	7.14	
Tourmaline (t=40°C)	9.09	3.79	
Zircon (t=40°C)	4.43	2.33	
	∥ to x axis	∥ to y axis	∥ to z axis
Brookite (t=17.5°C)	14.49	19.20	22.04

[1] $\alpha t^{\circ} = \frac{10^6}{l} \frac{\delta l}{\delta t}$ at t°C

where

l = length

and

t = temperature.

Most of the quartz of soils formed on sediments derived from the greywackes and schists of the South Island appears to be vein quartz and most grains exhibit strain. Fissured and incipiently fissured grains are abundant, the fissures being situated at the site of local strain or following the contact between adjacent units in granular quartz. In some grains fissures are filled with birefringent colloid, presumably the illite-montmorillonite colloid of the clay fraction of the soil. The swelling of such colloidal infilling of cracks may accelerate the disruption of an already fissured crystal. The penetration of an iron pan into an apparently homogeneous quartz stone or boulder is effected by the deposition of iron oxides from soil solutions in microfissures (fig. 1). Thin sections show that in some cases the iron hydroxide is deposited in a network of

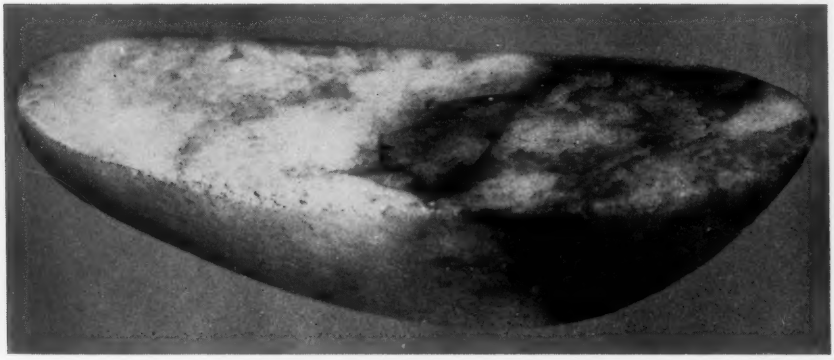

FIG. 1.—Pebble of vein quartz embedded in thin iron pan in podsol soil. The two parallel bands on the lower part (outside) of the pebble show the orientation of the pebble with respect to the iron pan. The polished upper surface of the pebble, a longitudinal section, shows the irregular manner in which the iron bearing soil solutions penetrated the pebble, apparently following the most accessible fissures. Enlarged 3.2×.

microfissures, mostly less than 3 microns wide.

Freezing of water in microfissures in the upper horizons of certain temperate and sub-arctic soils may also accelerate breakdown, but before this process can be effective the crystal must possess microfissures enlarged sufficiently to permit freezing of the contained water.

In thin sections of sandy soils formed on alluvium of mid-Pleistocene age, quartz grains occur in all stages of disintegration. The quartz in sand-sized grains is subrounded and almost exclusively vein quartz. Most of it is finely granular with a texture of granulation ranging from fine-silt sized to medium-silt sized. The coarsely granular quartz mostly shows strain effects as well. Most of the grains are fissured and some of them are completely disintegrated, the shattered fragments of the grain being in most cases separated by colloid matrix.

If the grains had been shattered before transportation they would not have survived the abrasion that rounded them, and if the shattering had taken place during preparation of the thin sections the colloid matrix would not have penetrated the fissures. It can safely be assumed, therefore, that the shattering took place in the soil.

Fragments of quartz rocks in the soils formed on the Moutere Gravels of Nelson Province are sufficiently disintegrated to be readily crushed to a fine sand between the fingers. This may be seen on the Nelson Moutere Road about 1 mile west of Redwoods Valley. In Central Otago examples of the breakdown of quartz may be seen in weathered schist at Chatto Creek, Butcher's Dam, and Galloway.

The disruption of quartz in this way may furnish an explanation of how soils of silt loam and fine sandy loam texture are derived directly from schists and greywackes in which polycrystalline vein quartz aggregates may exceed 1 cm in diameter in the shattered rock.

In rocks that have crystallised at temperatures exceeding the α/β inversion of quartz at normal pressures the transition from the low temperature form to the high temperature form may be a further disruptive force. This change takes place with a volume increase of 3.25 cc per kgm, or 0.86 percent by volume (Sosman, 1928). Fractures or stress acquired during inversion may be expected in the quartz of acid igneous rocks and in certain metamorphic rocks that have exceeded the inversion temperature during metamorphism. Holmquist (1911) claimed that prior strain determined whether quartz shattered on inversion and stated that homogenous quartz apparently survived intact. Wright and Larsen (1908) had already observed that metamorphic quartz was in fact shattered on inversion. It is possible, however, that shattering under these circumstances may be as much due to thermal expansion over the extended temperature range as to stress caused by the inversion. The schists and greywackes of the South Island of New Zealand have not exceeded the inversion temperature (D. S. Coombs, personal communication, 1958), but inversion shattering may be looked for in some of the acid igneous rocks of the North Island. Soil textures, in fact, reveal that the coarse quartz in the older rhyolite ash showers of the Central North Islands, e.g., the older showers from Lake Taupo, breaks down readily to silt sized particles in soils formed thereon, but that the quartz in the latest showers, e.g., the Kaharoa shower, is still intact (N. Z. Soil Bureau, 1954).

Solution

There is considerable literature referring to the solubility of silica but only a limited number of references to the solubility of quartz, many of them conflicting.

Although quartz appears to be the least soluble of the naturally occurring forms of silica as well as the most dense[5] (Moore and Maynard, 1929; Hitchen, 1945; and Krauskopf, 1956), its solubility may nevertheless be sufficient to make it worth taking possible loss from solution into consideration in soil studies. That quartz is appreciably soluble has been accepted for some time. The amount of silica transported annually to the sea which has been cited by Tarr (1917) and Clark (1924) as evidence of the solubility of quartz is, however, not acceptable. Much of this silica is derived from weathering of silicate minerals, and possibly only a small fraction comes from the solution

[5] The new artificial form coesite is more dense.

of quartz. Wahlstrom (1948), however, in a study of the weathering of granodiorite on Flagstaff mountain, recorded that quartz grains in the upper part of the weathered mantle were rounded and embayed and showed the effect of peripheral dissolution.

The solubility of quartz has been studied under a variety of conditions. Matignon and Marchal (1920) showed that appreciable quantities of silica can be dissolved from quartz by cold carbonated water, and Lovering (1923) found that water containing calcium and magnesium carbonates was an effective solvent of quartz, an observation later confirmed by Moore and Maynard (1929). Partial replacement of quartz by carbonates in sediments has been reported by Walker (1957).

Recent views on the solubility of silica have been summarised by Siever (1957). Although most of the recent solubility studies refer to amorphous silica, as for example, those of Alexander, Heston, and Iler (1954), Holt and King (1955), and Krauskopf (1956), values for the solubility of quartz have been reported from 1.6 mgm/100 ml at 20°C (Briscoe, Holt, Mathews, and Sanderson, 1936) to 30 ppm (Lenher, 1921). Siever (1957), using published free energy data, has derived a theoretical range of 7.25 to 14 ppm, which agrees reasonably well with the observed range of values.

It is likely that quartz crystals that have experienced local dislocation may have a greatly increased solubility at the site of the dislocation where the crystal will possess increased free energy and consequently proportionately greater solubility. The relationship between free energy and solubility is expressed by:

$$G = -RT \log k$$

where

G = free energy in kilocalories
T = temperature
R = constant for the particular substance

and

k = partial pressure of silica in solution, or the molecular concentration.

Since this is a logarithmic relationship a small increase in free energy will produce a large increase in solubility. Locally, a hundredfold increase in solubility may not be unlikely. The extension and enlargement of incipient cracks in quartz grains may thus be accelerated appreciably by solution. If the solution in contact with the grain contains any of the molecules known to increase the solubility of silica, e.g., magnesium or calcium carbonates (Lovering, 1923), solution could possibly be a dominant factor in the extension and opening up of incipient fissures.

The solubility of quartz rises with temperature (Gruner, 1930; Krauskopf, 1956) and solution is accordingly more important in the tropics than in temperate regions. Harrison (1933) has shown that in the weathering of granite in the humid tropics crystalline silica is dissolved in the upper horizons of the soil and redeposited lower down in the zone of disintegrating rock. The writer's observations of residual silica in the red and brown loams of North Auckland show that it consists of predominantly rounded unstrained grains.

Solution of quartz in soils changes not only the total amounts of quartz in the sand and silt fraction but also changes particle size distribution. Rate of solution is a linear function of specific surface and the finest particles will be removed completely while little change will have taken place in the largest particles. Jackson and others (1948) have pointed out that quartz solubility is a linear function of specific surface and therefore quartz may be expected and is found to decrease tenfold in quantity for each tenfold decrease in particle size of fraction considered. It was presumably partly for this reason that Jackson reversed Goldich's order of weathering for quartz and muscovite.

Both physical breakdown and solution are therefore likely to produce changes in the particle size distribution of quartz and solution is likely also to reduce its total quantity in a soil. Both processes are quite certainly slow but it must be remembered that except where soils have been constantly renewed because of erosion they approximate in age to that of the landscape on which they are formed, and recent studies in soil genesis have drawn attention to the fact that the age of many widespread soils

may be reckoned in many thousands of years. Ruhe and Scholtes (1956) have discussed the age of soils in relation to landscape in Iowa, and demonstrated that many date from Pleistocene times, and Thorp, Johnson and Reed (1951) have shown that some soils of the southern United States date from Pliocene times.

Because of its susceptibility to physical breakdown and solution, quartz can only be accepted as a stable mineral with certain reservations. It may be admissible as an index mineral in young soils, or in semi-arid soils with pH values below 7.0. In older soils or soils receiving higher rainfall careful consideration should be given to the nature of the quartz grains, whether they consist primarily of vein quartz or primary quartz, whether they show strain, or incipient or well defined fractures, and whether they show signs of solution. Quartz that showed any evidence of physical breakdown or solution would not be admissible as an index mineral.

GARNET

Garnets have been rated by some writers as resistant minerals and by others as unstable (Dryden and Dryden, 1946). Dana (1895) noted that garnets containing ferrous iron were particularly prone to disintegration. Milner (1923), Raeburn and Milner (1927), and Goldich (1938), however, ranked garnet as a stable mineral, comparable in stability with zircon and tourmaline. On the other hand, Bayley (1925) interpreted brown spots in the kaolins of North Carolina as chlorite and other micaceous minerals, stained brown with iron, and derived from the weathering of garnets. Allen (1948) believed that these brown spots were due to the weathering of garnets with high iron content and concluded that garnets of this kind were more easily decomposed than those low in iron. Humbert and Marshall (1943) provided supporting evidence for this view from their study of the weathering of acid and basic igneous rocks in Missouri. They showed that lime-iron garnets of the variety melanite and iron and manganese garnets from basic rocks appeared to be more weathered than garnets from granitic rocks.

Bramlette (1929) has pointed out that the etching that is characteristic of much detrital garnet has occurred in the soil since it has been superposed on rounding of the grains. This etching is a result of solution and indicates that local solution may be also a destructive factor.

Anomalous and variously oriented optical zones, which may be due to strain or to inversion to forms that are not strictly cubic, are widespread in detrital garnet, and would lead one to suppose that this mineral also may be subject to disruptive forces expressed along the margins of these zones.

Our present knowledge of the garnet group would therefore support the view that generalisations about the weathering of the group as a whole have no particular validity. Some of the members of the group may be sufficiently stable to serve as index minerals but there seems good reason to exclude garnets high in iron from the list. It is unfortunate that the individual members of the garnet group cannot be satisfactorily separated on the microscope stage from their optical properties alone: a chemical analysis is generally required. Further study of the weathering of the garnet group is therefore desirable before its exact position in the weathering sequence can be settled.

ZIRCON

Zircon has in the past been bracketed with tourmaline as one of the two most resistant minerals in soils. Recent work, however, has shown that zircon is not perfectly stable. Carroll (1953) has pointed out that although zircon has no natural cleavages it is nevertheless a brittle mineral, breaking readily into irregular fragments with conchoidal surfaces. It is apparently structurally weak where the change in direction of growth occurs at the junction of the prism and pyramid faces. Carroll concludes that zircon grains can, in fact, be reduced in size by the ordinary processes of weathering. Grains with numerous inclusions appear to be less stable than grains with few inclusions, and zoned grains less stable than unzoned grains. The hyacinth variety is less stable than normal zircon. It appears also that the disintegration of zircon may be accelerated by the penetration of soil solutions into microfissures and cavities. Micro-

fissures have been attributed by Hutton (1950) to strain induced by the change to the metamict state through the action of radiation, but they may occur apparently just as abundantly in normal zircons.

The mechanism by which rupture takes place near crystalline inclusions in zircon is not obvious. Crystallisation of zircon takes place at temperatures considerably above normal temperatures and strain would thus only be exerted at normal temperatures if the coefficient of expansion of the inclusion was less than that of zircon. Most common inclusions, however, possess coefficients of expansion greater than those of zircon as shown in table 1.

Inclusion cavities that were first filled with fluid under temperatures and pressures that prevailed during crystallisation, will be under reduced pressure at normal temperatures and pressures and are therefore not likely to cause strain (Ingerson, 1955).

An examination of the zircons in the loess soils of the South Island of New Zealand has shown that microfissures are more abundant in grains with inclusions than in grains without inclusions and are particularly abundant and destructive in grains with large inclusions. In many grains containing a large inclusion the orientation of the microfissure is consistent with stress caused by the inclusion. It is also true that at sites of local stress the dislocated lattice will have a greater solubility because of the greater free energy at the site of the stress. This has been discussed more fully with reference to quartz and may explain the solution pits that occur in many zircons in New Zealand soils in close proximity to inclusions. In some grains the solution pit has penetrated to the inclusion and partly destroyed it. The crystalline inclusions that seem to be most productive of solution pits have not been identified with certainty but appear to consist of quartz, apatite and rutile, and iron ores (Brammal, 1928).

Many zircons with abundant inclusions and most crystals with extensive fissures or fractures show abnormal optical properties, presumably as a result of strain, and the crystal shows a biaxial interference figure. In some crystals the figure changes from one part of the crystal to another. Most crystals showing no optical anomalies and containing few or no inclusions show no solution pits and no cracks.

The solubility of normal zircon may possibly be appreciable in certain circumstances. Carroll (1953) concludes that "zircon may be slightly soluble in Ca-bicarbonate or Na-bicarbonate. Observations on a number of zircon grains from different localities suggest acid as well as alkaline leaching, as in soil formation, acting through long periods of time, for the production of corrosion and the final removal of zircon." Carroll also concluded that "The use of zircon as an indicator of changes in a soil profile based solely on the chemical determinations of zirconium should be interpreted with caution, but varietal features of the actual zircon grains in a heavy residue from a soil could be used with advantage. Perhaps a combination of chemical and microscopic determinations should be expected to give the most correct and satisfactory results in studies on soil development." The writer would add the further qualification that zircon should not be used as an index mineral in studies of soil development where the soils have formed on old landscapes where a high proportion of the crystals show abundant crystalline inclusions, local or general optical anomalies, interference figures, or incipient cracking. Possibly the hyacinth variety of zircon should be rejected if many grains show the system of cracks radiating from dark brown or opaque inclusions described by Hutton (1950) and attributed by him to radiation effects.

CONCLUSIONS

An absolute scale of stability for the so-called resistant minerals about which all mineralogists and pedologists would agree is still wanting. It may be that a satisfactory scale can only be prepared for a particular environment. Such a scale, however, would still not be absolute and there could be wide departures from the scale because of physical imperfections in the mineral grains, such as strain or the inclusion of crystalline minerals with coefficients of expansion markedly different from that of the containing mineral, or variations in the composition of the mineral. It must also be remembered that a stable mineral may be weathered to a

greater extent in an old soil than a much less stable mineral in a younger soil. In place of a completely satisfactory order of stability for soil index minerals, a somewhat empirical order must be accepted, and the physical and chemical stability of any minerals chosen for a particular study should be carefully assessed in the environment in question before they are regarded as acceptable for reference purposes.

In soil studies that concern particle size distribution of minerals in the silt and sand sized ranges the minerals quartz, garnet, and possibly zircon should not be used as index minerals in the following circumstances:

(1) in soils on old land surfaces. Discrepancies between the texture of the parent material and that of the soil are not uncommon on such landscapes,
(2) in soils that have existed for long periods under high rainfall, especially in the wet tropics,
(3) where the minerals contain abundant inclusions, and especially where the inclusions are large or with markedly different coefficients of expansion from those of the parent mineral grain,
(4) where the mineral grains show extensive strain or incipient fissuring,
(5) where garnet is to be used as an index mineral and the chemical analysis shows it to be a high iron garnet.

REFERENCES

ADAMS, J. E., AND MATELSKI, R. P., 1955. Distribution of heavy minerals and soil development in Scott silt loam: Soil Sci., v. 79, p. 59–69.

ALLEN, V. T., 1948, Weathering and heavy minerals: Jour. Sedimentary Petrology, v. 18, p. 38–42.

ALEXANDER, G. B., HESTON, W. M., AND ILER, R. K., 1954, The solubility of amorphous silica in water: Jour. Phys. Chem. v. 58, p. 453–457.

BARSHAD, I., 1955, Soil development, *in* Chemistry of the soil. Firman E. Bear, Ed., Reinhold, New York.

BAYLEY, W. S., 1925, The kaolins of North Carolina: North Carolina Geol. and Econ. Survey Bull. no. 25.

BLANCK, E., 1949, Einführung in die Genetische Bodenlehre. Vandenhoeck and Ruprecht, Göttingen, 420 p.

BRAMLETTE, M. N., 1929, Natural etching of detrital garnet: Am. Mineralogist, v. 14, p. 336–337.

BRAMMALL, A., 1928, Dartmoor detritals: a study in provenance: Proc. Geol. Soc. London, v. 39, p. 27–48.

BRISCOE, H. V. A., HOLT, P. F., MATTHEWS, JANET W., AND SANDERSON, PHYLLIS M., 1936, Some new properties of certain industrial dusts: Trans. Inst. Min. and Met., v. 46, p. 291–302.

BRYAN, W. H. AND TEAKLE, L. J. H., 1949, Pedogenic inertia, a concept in soil science: Nature, v. 164, p. 969–971.

CARROLL, D., 1953, Weatherability of zircon: Jour. Sedimentary Petrology, v. 23, p. 106–116.

CLARK, F. W., 1924, The data of geochemistry; U.S. Geol. Survey. Bull. 770, 841 p.

CLARKE, J. R., 1927, Density and thermal expansion of chemical compounds in the crystalline state, under atmospheric pressure *in* International critical tables, v. 3, p. 43.

DANA, E. S., 1895, The system of mineralogy of James Dwight Dana. 6th ed., New York.

DRYDEN, L., AND DRYDEN, C., 1946, Comparative rates of weathering of some common heavy minerals: Jour. Sedimentary Petrology, v. 16, p. 91–96.

GOLDICH, S., 1938, A study of rock weathering: Jour. Geology, v. 46, p. 17–58.

GRUNER, J. W., 1930, Hydrothermal oxidation and leaching experiments; their bearing on the origin of Lake Superior haematite-limonite ores: Econ. Geol., v. 25, p. 697–719.

HARRISON, J. B., 1933, The katamorphism of igneous rocks under humid tropical conditions. Imperial Bureau of Soil Science, Harpenden, 79 pp.

HASEMAN, J. F., 1944, An investigation of the use of heavy minerals in determining the origin and course of profile development in soils. University of Missouri Thesis; Abstract *in* Biol. abstracts, 1945, p. 2171.

HASEMAN, J. F. AND MARSHALL, C. E., 1945, The use of heavy minerals in studies of the origin and development of soils: Univ. of Missouri Research Bull. no. 387, 75 p.

HITCHEN, C. S., 1945, The "solubility " of silica: Econ. Geol., v. 40, p. 361–365.

HOLMQUIST, P. J., 1911, Über die Bildung von Tridymite und Cristobalite in Quartz Ziegeln: Geol. Fören. Stockholm Förh., v. 33, p. 245–260.

HOLT, P. F. AND KING, D. T., 1955, The chemistry of silica surfaces: Jour. Chem. Soc., p. 773–779.

HUMBERT, R. P. AND MARSHALL, C. E., 1943, Mineralogical and chemical studies of soil formation from acid and basic igneous rocks in Missouri: Univ. of Missouri Res. Bull. no. 359, 60 p.

HUTTON, C. O., 1950, Studies of heavy detrital minerals: Geol. Soc. America Bull., v. 61, p. 635–710.

IDDINGS, J. P., 1906, Rock minerals. John Wiley & Sons, Inc., New York, 548 p.

INGERSON, E., 1955, Methods and problems of geologic thermometry: Econ. Geol., Fiftieth Anniv. v. 341–410.
JACKSON, M. L., TYLER, S. A., WILLIS, A. L., BOURBEAU, G. A., AND PENNINGTON, R. P., 1948, Weathering sequence of clay-sized minerals in soils and sediments: Jour. of Phys. and Colloid Chem., v. 52, p. 1237–1260.
JOFFE, J., 1949, Pedology. 2nd ed. New Brunswick, 662 p.
KRAUSKOPF, K. B., 1956, Dissolution and precipitation of silica at low temperatures: Geochim. et. Cosmochim. Acta, v. 10, p. 1–26.
LENHER, V., 1921, Silicic acid: Jour. Amer. Chem. Soc., v. 43, p. 391–396.
LOVERING, T. S., 1923, The leaching of iron protores: solution and precipitation of silica in cold water: Econ. Geol. v. 18, p. 523–540.
MARSHALL, C. E., 1940, A petrographic method for the study of soil formation: Soil Sci. Soc. Amer. Proc., v. 5, p. 100–103.
MARSHALL, C. E. AND HASEMAN, J. B., 1943, The quantitative evaluation of soil formation and development by heavy mineral studies: Soil Sci. Soc. Amer. Proc., v. 7, p. 448–453.
MATIGNON, C. AND MLLE. MARCHAL, 1920, Action prolongée de acide carbonique sur les silicates et le quartz: Compt. Rend., v. 170, p. 1184–1186.
MERRILL, G. P., 1897, A treatise on rocks, rock-weathering and soils: 1st ed., New York, 411 p.
MILNER, H. B., 1923, The study and correlation of sediments by petrographic methods: Mining Mag., v. 28, p. 80–92.
MOORE, E. S., AND MAYNARD, J. E., 1929, Solution, transportation and precipitation of iron and silica: Econ. Geol., v. 24, p. 272–303.
N. Z. SOIL BUREAU, 1954, General survey of the soils of North Island, New Zealand; N. Z. Soil Bur. Bull. (n.s.) 5, 286 p.
PETTIJOHN, F. J., 1941, Heavy minerals and geologic age: Jour. Geol., v. 49, p. 610–625.
POLYNOV, B. B., 1937, The cycle of weathering. Thomas Murby, & Co., London, 220 p.
RAEBURN, C. AND MILNER, H. B., 1927, Alluvial prospecting. Thomas Murby & Co., London.
RUHE, R. V. AND SCHOLTES, W. H., 1956, Ages and development of soil landscapes in relation to climatic and vegetational changes in Iowa: Proc. Soil. Sci. Soc. Amer., v. 20, p. 264–273.
RUSSELL, E. J., 1950, Soil conditions and plant growth. 8th ed., London, 635 p.
SIEVER, R., 1957, The silica budget in the sedimentary cycle: Am. Mineralogist, v. 42, p. 821–841.
SOSMAN, R. B., 1928, Silica, *in* International critical tables: National Res. Council. McGraw-Hill Book Co., Inc., New York.
TARR, W. A., 1917, Origin of chert in the Burlington Limestone: Amer. Jour. Sci., v. 44, p. 409–452.
THORP, J., JOHNSON, W. M. AND REED, E. C., 1951, Some post-Pliocene buried soils of the central United States: Jour. Soil Sci., v. 2, p. 3–19.
TURNER, F. J., 1942, Structural petrology of quartzose veins in the schists of Eastern Otago—Part I: Trans. Roy. Soc. New Zealand, v. 71, p. 307–324.
WAHLSTROM, E., 1948, Pre-formation and recent weathering on Flagstaff Mountain near Boulder, Colorado: Geol. Soc. America Bull., v. 59, p. 1173–1189.
WALKER, T. R., 1957, Frosting of quartz grains by carbonate replacement: Geol. Soc. America Bull., v. 68, p. 267–268.
WRIGHT, F. E. AND LARSEN, E. S., 1908, Quartz as a geological thermometer: Amer. Jour. Sci., v. 27, p. 421–447.

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FIGS. 1–3, DECEMBER, 1959

PETROLOGY AND SOURCE OF SEDIMENTS IN THE NARRAGANSETT BASIN OF RHODE ISLAND AND MASSACHUSETTS[1]

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ABSTRACT

The Narragansett Basin, a Pennsylvanian epieugeosyncline, contains five lithologic units, the most extensive of which is the Rhode Island Formation. The rocks of the Basin are predominantly sandstone and conglomerate and all are of continental origin. Lithic graywacke is the common sandstone type and the poorly sorted conglomerates are made up mostly of quartzite roundstones. Cross-stratification and the orientation of plant fossils indicate that the major source area for the sediments of the Narragansett Basin lay to the northeast.

INTRODUCTION

The purpose of the present study is to examine the primary sedimentary features of the rocks of the Narragansett Basin in an effort to reconstruct the pattern of current movement, and to study the petrography of these rocks for clues to conditions within the source areas and to environment of deposition.

Geographically, the Narragansett Basin covers most of eastern Rhode Island and extends into Massachusetts. It is elongated in a northeast-southwest direction and is approximately 60 miles long and 20 miles wide. The northernmost extremity of the Basin is 10 miles southwest of Massachusetts Bay, and its southernmost extremity extends directly into the Atlantic Ocean. An extensive cover of glacial drift blankets the area and thus bedrock outcrops are sparse.

STRATIGRAPHY

General Geologic Relations

The Narragansett Basin is surrounded and underlain by rocks of plutonic and metamorphic origin. Granitic rock types are greatly predominant. The metamorphic rocks crop out mostly on the western side of the Basin and most of them belong to the Precambrian or early Paleozoic Blackstone Series (Quinn, 1953, p. 266). Within the margins of the Basin older rocks are exposed in two areas. At Hoppin Hill, Massachusetts, the Precambrian Dedham granodiorite is overlain by Lower Cambrian slates. At Bristol, Rhode Island, granite gneiss and quartz-mica schist are exposed (Quinn and Springer, 1954).

The sedimentary rocks of the Basin include monotonous sequences of conglomerate, sandstone, and shale. All are continental in origin, and, on the basis of plant fossils, all have been assigned to the Pennsylvanian System. Five lithologic units are mappable. Because of abrupt facies changes, complex structures, and extensive cover of glacial deposits close stratigraphic correlations are exceedingly difficult and only the broadest stratigraphic relationships have been determined.

Intraformational correlation, even within short distances, is difficult. This may be attributed to the scarcity of fossils and marker beds, and to the rapid lateral and vertical changes that are so typical of the fluviatile environment.

Pondville Conglomerate

The Pondville Conglomerate, the oldest of the formations within the Narragansett Basin, rests unconformably on the pre-Pennsylvanian plutonic and metamorphic rocks. This unit, 100 to 160 feet thick (Quinn, 1953, p. 267), is a discontinuous basal conglomerate that crops out along the margins of the Basin. The formation is heterogeneous in composition with the roundstones consisting primarily of quartzite and granite. Quartzite is predominant in most areas. The conglomerate is poorly sorted, exhibiting wide ranges in the size of the constituents.

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Wamsutta Formation

Overlying the Pondville in the northern part of the Basin, but partly equivalent to it, is the Wamsutta Formation. This formation is composed of red conglomerate, sandstone, and shale, the color of which may be attributed to red iron oxide probably of predepositional origin. Intercalated with these red beds in the vicinity of South Attleboro, Massachusetts are layers of basalt and rhyolite and a discontinuous thin bed of fresh-water limestone.

Compositionally, the conglomerates are heterogeneous and, in general, very poorly sorted. Boulders as much as 4 feet in length have been noted. Quartzite is the principal clastic constituent, but granite, rhyolite, vein quartz, and metamorphic rock fragments are also present. The red coloring of the particles occurs as an iron oxide surface stain. The sandstones are normally of the graywacke type but are locally arkosic. Ferruginous cement is present in all samples. The shales are also ferruginous and locally contain poorly preserved plant fragments.

Rhode Island Formation

Of all the rock units in the Narragansett Basin, the Rhode Island Formation is by far the thickest and most extensive.

In many places the Rhode Island Formation rests directly on the pre-Pennsylvanian basement rocks, but it also overlies the Pondville Conglomerate in some areas. In the northwestern portion of the Basin it interfingers with and overlies the Wamsutta Formation. The thickness of this unit has been estimated by Shaler, Woodworth, and Foerste (1899, p. 134) to be approximately 10,000 feet.

The Rhode Island Formation is made up of thick sequences of conglomerate, sandstone, shale, and meta-anthracite. The conglomerate beds are heterogeneous in composition with the predominant particles consisting of quartzite and granite. Quartzite is by far the most common constituent, but Page (1930) stated that granite pebbles may make up as much as 25 percent of the total. Sandstone, shale, schist, and quartz fragments are common in most places. In many outcrops the matrix constitutes up to 50 percent of the rock but in other areas the pebbles and cobbles are tightly packed together.

The conglomerates are poorly sorted and the range in the size of the particles is great. It is difficult to estimate an average size, but it may be ventured that the average longest diameter approaches 3 inches. Extreme gradations in roundness and sphericity occur. The conglomerates, in the terminology of Krumbein and Sloss (1951, p. 128), are of the graywacke type.

Sandstone is the most prevalent rock type in the Rhode Island Formation, and it is in this rock type that the majority of the sedimentary features are found.

Following the classification of Pettijohn (1957a, p. 291), the sandstones of the Rhode Island Formation are of three types: lithic graywacke, subgraywacke, and subarkose. Lithic graywacke, by definition, contains less than 75 percent quartz and more than 15 percent matrix. In subgraywacke the matrix is absent or scanty, being less than 15 percent. In the detrital fraction of both of these types the rock fragments exceed the feldspars. Subarkose contains from 75 to 95 percent quartz, less than 15 percent matrix, and the feldspars exceed the rock fragments.

Lithic graywacke is the prevailing sandstone type in the Rhode Island Formation. The average quartz content of this rock is 32 percent as determined from thin section analyses, the results of which are shown in table 1. The quartz grains exhibit low roundness values and large gradations in sphericity occur. Strained quartz showing undulatory extinction is abundant in all samples.

The feldspars are distinctly subordinate with the average content being about 5 percent, although casual megascopic inspection suggests a higher percentage. In general, potassium feldspars exceed those of the plagioclase group. The feldspars are weathered showing partial alteration to chlorite and sericite.

Matrix is the most abundant constituent in the lithic graywacke. On the average it comprises 34 percent of the total. Many mineral and rock fragments are completely surrounded by it. The matrix is composed essentially of chlorite, sericite, and finely disseminated quartz.

Rock fragments also constitute an important percentage of the lithic graywacke.

TABLE 1.—*Petrographic analyses of sandstones from the Narragansett Basin*

Rock type[1]	Quartz	Feldspar	Matrix	Rock Fragments	Mica	Accessory Minerals
Lithic graywacke	27.0	4.0	44.6	22.6	1.3	1.5
Lithic graywacke	23.8	6.8	41.1	22.8	1.5	4.0
Lithic graywacke	22.2	1.5	35.4	38.3	0.3	1.3
Lithic graywacke	23.2	5.8	35.2	34.1	0.9	0.8
Lithic graywacke	28.6	1.0	37.7	15.8	11.5	5.5
Lithic graywacke	37.2	0.6	44.3	10.5	5.9	1.5
Lithic graywacke	34.2	5.1	40.6	13.7	3.8	2.6
Lithic graywacke	34.1	6.5	39.2	14.2	2.5	3.4
Lithic graywacke	33.0	1.1	42.4	15.6	5.5	2.4
Lithic graywacke	34.8	9.4	32.1	15.0	3.7	4.0
Lithic graywacke	36.5	11.0	22.2	28.3	1.4	0.6
Feldspathic graywacke	42.6	14.2	26.2	12.1	3.3	1.6
Lithic graywacke	41.3	9.1	30.0	10.8	4.2	4.5
Lithic graywacke	34.6	6.7	24.2	19.2	13.6	1.7
Lithic graywacke	36.4	5.4	29.2	19.7	8.1	1.3
Lithic graywacke	29.3	4.0	32.0	31.3	1.6	1.8
Lithic graywacke	40.5	2.7	32.0	18.7	4.3	1.9
Subgraywacke	63.3	1.0	25.0	2.4	6.0	2.3
Subgraywacke	64.1	2.4	5.4	4.5	22.2	1.4
Subarkose	78.0	4.4	1.0	1.0	14.2	1.4

[1] Classification of Pettijohn (1957).

The average for the Rhode Island Formation is 19 percent. Under the microscope the following rock types were noted: (1) quartzite, (2) chlorite schist, (3) quartz-muscovite schist, (4) shale, (5) fine-grained volcanics, and (6) granitic types.

A noteworthy characteristic of the rock fragments, in general, is that they are well rounded but show low sphericity values. The average rock fragment is elongate. This is especially noticeable in the schistose fragments, and the schistosity in these rocks runs parallel to the maximum elongation direction of the fragment itself. This is to be expected in view of the fact that the plane of greatest weakness in rocks of this type is also parallel to the schistosity. The quartzitic fragments were more nearly equidimensional.

The micas form a very small portion of the lithic graywacke in the Narragansett Basin, although field examination suggests a greater importance. Muscovite is the prevalent type and detrital biotite is rare. Biotite of metamorphic origin becomes increasingly common in the subgraywacke and subarkose of the more southerly exposures.

The accessory minerals in the sandstones of the Rhode Island Formation are chiefly magnetite, zircon, ilmenite, and apatite.

The shales of this formation are mostly black, but gray and greenish varieties are found locally. The black shales commonly contain concretions and associated pyrite cubes.

The coal of the Narragansett Basin is meta-anthracite that is found in beds ranging up to 30 feet in thickness. The principal inadequacies of this coal are its high ash content (commonly greater than 25 percent) and its low content of volatile matter (Quinn and Oliver, in press; Quinn and Glass, 1958).

Dighton Conglomerate

The Dighton Conglomerate occurs in three principal areas in the Narragansett Basin. The three areas are synclinal in structure and from northwest to southeast are named the Attleboro, Taunton, and Dighton synclines respectively. Woodworth (Shaler, Woodworth, and Foerste, 1899, p. 184) suggests that the thickness of this formation approaches 2000 feet.

The Dighton appears to occupy the highest stratigraphic position of the formations now present in the Basin. In the extreme southern portion of the Basin near Newport, Rhode Island, a very coarse conglomerate

referred to as the Purgatory Conglomerate is exposed in a restricted area. Both the Dighton and the Purgatory are devoid of characteristic fossils and for this reason the stratigraphic relationship between the two is not exactly known. Perkins (1920, p. 65) suggested the equivalence of these formations, but there is little evidence for this. Furthermore, the stratigraphic equivalence of the rocks within the three previously mentioned synclines has not been demonstrated. Slight lithologic similarity between these areas suggests equivalence, but this is not a reliable means of correlation. Finally, the Dighton Conglomerate may well be a coarse conglomeratic facies of the Rhode Island Formation with which it is apparently conformable.

In composition the Dighton Conglomerate is heterogeneous. The pebbles and cobbles are composed of quartzite, granite, quartz, and widely scattered pebbles of other metamorphic and volcanic rocks (mostly schists and felsites). Quartzite averages 70 percent of all of the roundstones present (Page, 1930). Some of the quartzite roundstones contain the Upper Cambrian or Lower Ordovician brachiopod *Obolus* (Shaler, Woodworth, and Foerste, 1899, p. 382). The matrix of the conglomerates was studied by Perkins (1920, p. 67) who found it to be a poorly sorted combination of quartz, quartzite, feldspar, kaolin, muscovite, and biotite.

Many sandstone lenses have been observed in the Dighton, and on the basis of composition they are classified as lithic graywacke. Conglomeratic sandstones were also noted, but no occurrences of shale that can be definitely assigned to this formation were seen.

In texture, the Dighton Conglomerate is poorly sorted and this, together with its heterogeneous composition, places it under the heading of a graywacke conglomerate (classification of Krumbein and Sloss, 1951). The pebbles and cobbles display moderate roundness and sphericity. The size range is great and according to Page (1930) the largest fragments reach " . . . . a measured maximum of 24 inches in their greatest diameter and 11 inches in the least." The most common longest diameter is about 4 inches.

Purgatory Conglomerate

The Purgatory Conglomerate occurs in small areas near Newport, Rhode Island in the extreme southeastern portion of the Narragansett Basin. The thickness of the formation is estimated by Shaler, Woodworth, and Foerste (1899, p. 374) to be from 450 to 600 feet. This conglomerate may be the uppermost unit in the southern part of the Basin and according to Foerste (1899, p. 374), it is gradational with the underlying Rhode Island Formation.

In composition and texture the Purgatory is homogeneous and well sorted. Of the roundstones, 95 percent are quartzite and 5 percent are granite (Perkins, 1920, p. 68). The formation is extremely coarse with the roundstones being from 10 to 20 inches or more in longest diameter. The roundness is good. The cobbles and boulders have been aligned and stretched in a north-south direction by structural pressures, and since the matrix is very scanty they commonly indent each other.

Rare sandstone lenses occur interbedded with the coarse conglomerate and locally these exhibit cross-stratification. No shale beds have been reported from this formation.

CROSS-STRATIFICATION

Classification

The terminology of McKee and Weir (1953) will be followed in classifying the cross-stratification of the Narragansett Basin. This classification is based on physical characteristics rather than on mode of origin. The terms "cross-bedding" and "cross-lamination" have a quantitative thickness connotation and therefore should be used only where applicable.

All the cross-stratification within the Basin is of the trough type. This type is defined as "any set of cross-strata whose lower bounding surface is a curved surface of erosion" (McKee and Weir, 1953, p. 385). The "festoon cross-lamination," first described by Knight (1929), is a variety of the trough cross-stratification, but it must not be considered as the only variety. McKee and Weir (1953, p. 387) define the festoon variety as consisting of ". . . essentially elongate semiellipsoidal troughs that crosscut each

other so that only parts of each unit are preserved, and, in section a festoon-like appearance results." In the Narragansett Basin the festoon variety is rare, occurring locally in only two areas.

The magnitude of the trough cross-stratification in the Narragansett Basin ranges from small scale (cross-strata less than 12 inches in length) to medium scale (cross-strata from 1 to 20 feet in length). The shape of the cross-stratification sets is lenticular and the cross-strata themselves are predominantly concave, that is, the single layers bend downward. In thickness the cross-stratification ranges from cross-laminated (1 cm to 2 mm) to very thinly cross-bedded (5 cm to 1 cm).

Inclinations

The inclination of cross-strata is a function of the angle of repose of the material at the time of deposition. Van Burkalow (1945) has shown that several variables work to determine what the angle of repose will be. The most important of these are: (1) shape of the fragments, (2) sorting of the fragments, and (3) moisture. The shape of the fragments affects the angle of repose by lowering it as sphericity and roundness increase. In poorly sorted material, the greater the average particle size, the greater the angle of repose. Water in excess of saturation reduces the angle of repose. McKee (1955, p. 59) came to a similar conclusion concerning the effect of moisture. He stated, "For any particular variety of sand . . . the maximum slope under aeolian conditions is consistently greater than that under subaqueous conditions." He found that under subaqueous conditions, the greatest angle of repose was around 32 degrees for sand-sized particles and that when clay-sized particles were mixed with the sand the angle of repose was lowered.

The histogram in figure 1 shows the distribution of the cross-stratification inclinations in the rocks of the Narragansett Basin. The mode lies between 10 and 14 degrees. The arithmetic mean inclination is approximately 13 degrees. A low mean inclination is to be expected in view of the conditions in operation at the time of deposition. The factors involved in reducing the angle of repose were probable temporary

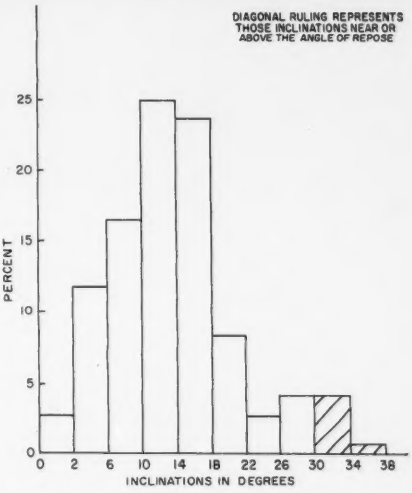

FIG. 1.—Histogram showing cross-stratification inclinations.

saturation with water in the fluviatile environment plus poor sorting of the lithic graywacke with an abundance of clay-sized particles in the matrix.

After correction for tilt by means of the stereonet it is occasionally found that in folded sediments the cross-strata assume angles that are larger than the greatest angle of repose. Pettijohn (1957b, p. 474) has suggested that the cross-strata in such cases have been rotated by deformation. In the Narragansett Basin only a few of the inclinations assume angles steeper than the greatest angle of repose and it is probable that these may be due to errors in measurement.

Azimuths

The data on the azimuths (dip direction) of the cross-strata in the sandstones of the Narragansett Basin total 60 readings that represent 11 different geographical areas located in 6 quadrangles. The exposures from which the data were derived are concentrated in the middle portion of the Basin. Outcrops are extremely scarce to the north, and to the south the increased metamorphism tends to obscure primary sedimentary features. Figure 2 illustrates the

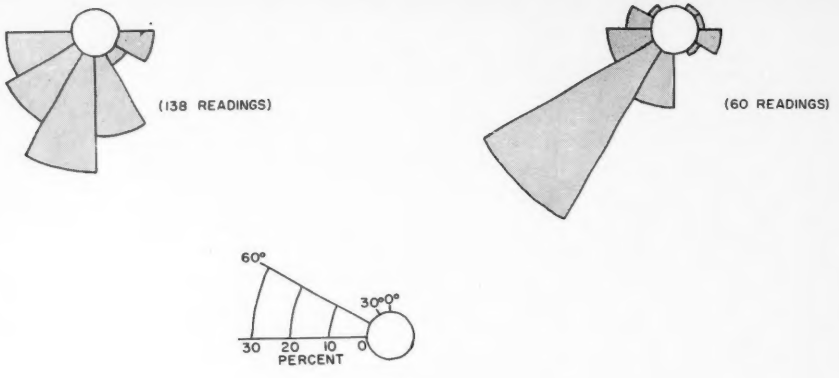

FIG. 2.—Circular histograms showing cross-stratification azimuth distribution (right) and azimuth distribution of fossil plant alignment (left).

distribution of the azimuths plotted in the form of a circular histogram. Eighty percent of the readings lie in the southwest quadrant. The mean azimuth for all of the data is 218 degrees (S38°W) and the distribution is distinctly unimodal.

ALIGNMENT OF FOSSIL PLANTS

Introduction

The alignment of fossil plants and animals has been used as an aid in determining current-flow direction by Cloos (1938), Kay (1945), King (1948), Crowell (1955), Kuenen and Sanders (1956), and others.

Unlike cross-stratification, the lineation of fossil plants does not provide the sense of current flow. If, for example, a suite of fossil plants is aligned in a north-south direction the observer can only state that the current moved either from north to south or from south to north. Consequently, such lineation is of little value unless it is corroborated by cross-stratification or some other specific primary feature. In fact then, the alignment of fossils may be used only in conjunction with other evidence.

The plant fossils of the Narragansett Basin occur as casts or impressions in the sandstones and shales of all the formations except the Pondville and Purgatory Conglomerates. The plants that were used as directional indicators were *Calamites* and *Sigillaria*, with the latter being only rarely observed. The length of the stems ranges from several inches to 10 feet. The smaller stems invariably occur together in groups, whereas the larger "trunks" are more widely scattered. The smaller fragments lie, as a rule, in the plane of the bedding while the larger fragments are commonly inclined to that plane.

No plant fossils were found directly associated with cross-stratification. The significance of this observation is not clear, but it may be that conditions were changing so rapidly in areas where cross-stratification occurs that preservation of organic remains was not favored.

Azimuths

The data on lineation of fossil plants consist of 138 readings from 10 different geographical areas located in 5 quadrangles. The azimuths have been placed in the southern quadrants of the circular histogram in figure 2. This arbitrary placement into the southern quadrants is justified here because the data are supporting evidence to the cross-stratification azimuths that have already defined the trend.

Of the total plant fossil azimuths, 66 percent fall in the southwest quadrant. The distribution is unimodal but skewed slightly

toward the southwest. The mean azimuth of the 138 readings is 193 degrees (S13°W). This is in close agreement with the mean of the cross-stratification azimuths which is 218 degrees (S38°W). The combined evidence results in an overall mean azimuth of 201 degrees (S21°W).

PALEOENVIRONMENTAL INTERPRETATIONS

Position and Composition of Source Areas

In dealing with an intermontane basin it would be expected that streams would enter the basin more or less equally from all sides. In general, such is not the case in the Narragansett Basin. Although the available directional data are few, the evidence points strongly to a source area lying to the northeast. The mean direction indicated by the cross-stratification is S38°W, and by the orientation of fossil plants is S13°W. The combined mean current direction suggests that the source area for many of the sediments was located to the northeast. This should not be construed to mean that the source of the Rhode Island Formation was located entirely in one area. Quite obviously in a basin of this type sediments will be derived from many geographically varied sources. However, it appears that one principal source to the northeast prevailed.

It is a well-known fact that the petrography of a sedimentary rock often reflects the petrography of the area from which it was derived. Thus from a petrographic examination of the rocks of the Rhode Island Formation certain statements can be made concerning the composition of the source area. The presence of detrital quartz exhibiting undulatory extinction suggests derivation from a metamorphic terrain (Pettijohn, 1957a, p. 119). This is supported by the scarcity of feldspars and the abundance of lithic fragments of metamorphic types. Furthermore, the many quartzite roundstones in the conglomerates of all the formations point to a metamorphic source. Many of these roundstones contain several species of *Obolus*, a phosphatic inarticulate brachiopod. Walcott (1898, p. 327) correlated these forms with those of the Lower Ordovician or Upper Cambrian rocks of Great Belle Island, Newfoundland.

A source area composed dominantly of metamorphic rock types is in marked contrast to the rocks that surround and underlie the Narragansett Basin today. With the exception of some small occurrences of the metamorphic Blackstone Series which crops out to the west, rocks of granitic types (granite and granodiorite) surround the Basin on three sides. The granitic rocks around the margin of the Basin apparently did not make important contributions to the sediments, except on a local scale in the Pondville Conglomerate.

The source for many of the Narragansett Basin sediments was an uplifted landmass composed in part of probable Cambrian and Ordovician quartzites and schists located to the northeast of the present extent of the Basin. An obvious exception to this is the rocks of the Wamsutta Formation. Because this formation is composed of red beds it lies in marked contrast to all the other formations. Since it is red and since it interfingers with the Rhode Island Formation its source necessarily lies to the north and northwest of its present northern location (fig. 3).

Environment of Deposition

Tectonic framework.—In the terminology of Kay (1951), the Narragansett Basin is an epieugeosyncline. This type of basin has been defined (Kay, 1951, p. 107) as ". . . deeply subsiding troughs with limited volcanism associated with rather narrow uplifts and overlying deformed and intruded eugeosynclines." These strongly negative areas are characterized by rapid subsidence and rapid deposition. In a non-marine area such as the Narragansett Basin this is reflected by the occurrence of thick sequences of "poured-in" lithic graywacke, arkose, and graywacke conglomerate showing typical fluvial sedimentary features such as cross-stratification and scour-and-fill channel deposits. The coarseness of the conglomerates and their presence throughout the section indicates an adjacent source of considerable relief located in an area of crustal unrest. The occurrences of coal and black shale indicate stagnant conditions in floodplains and swamps.

Climate.—The red beds of the Wamsutta Formation and the coal, with its associated plants, of the Rhode Island Formation com-

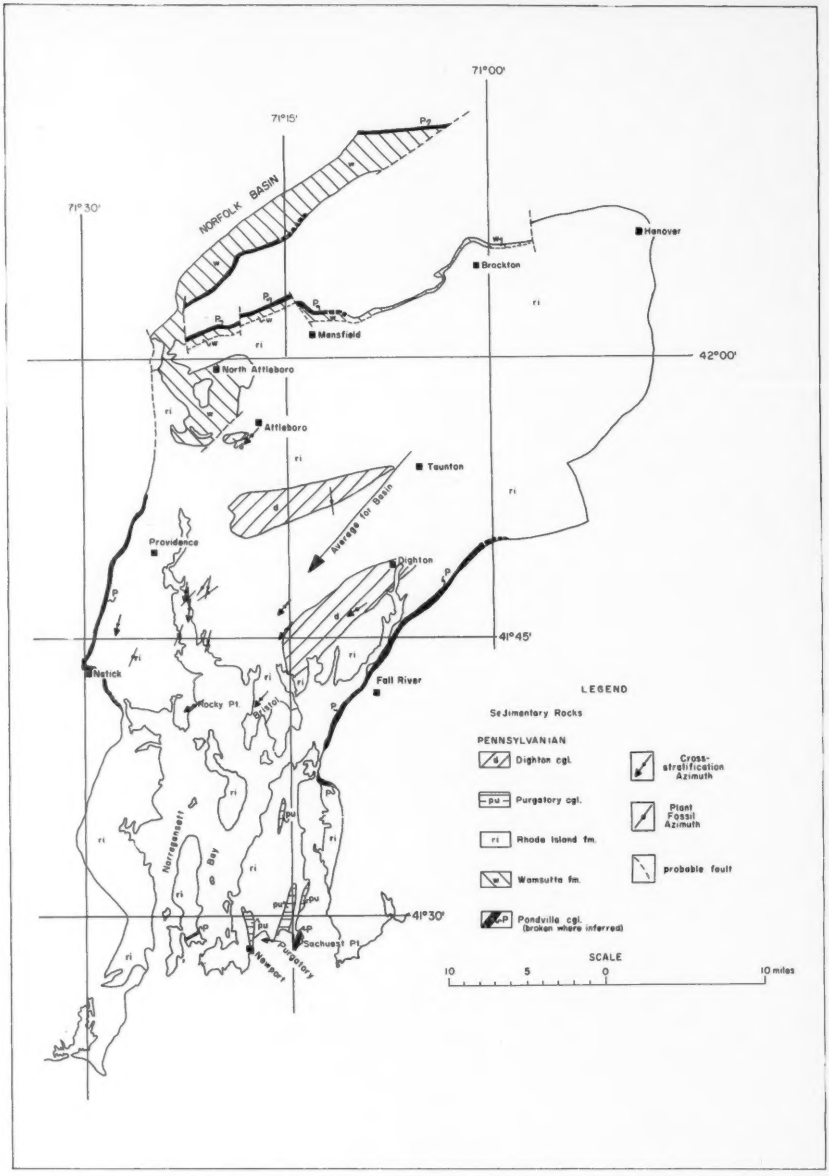

FIG. 3.—Geologic map of the sedimentary rocks of the Narragansett Basin showing cross stratification and plant fossil azimuths. (Base map modified after Quinn and Oliver, in press.)

bine to form a basis for climatic reconstruction.

The mere presence of coal and abundant plant fossils indicates a moist climate, and the red beds of the Wamsutta Formation provide a clue towards interpretation of temperature. The work of Krynine (1950), Van Houten (1948), and others indicates that red soils typically form under warm, humid conditions. In the Narragansett Basin a warm, humid climate existed that was conducive to the formation of peat in the poorly drained areas, and of red soils in certain well-drained uplands. Inasmuch as the flow was predominantly to the south, the northern areas were higher and better drained and presumably were oxidizing environments, thus preserving the red color. Those sediments carried into the more southerly reducing environments lost their red color. As sedimentation proceeded, the reducing environment covered the entire basin and either no red beds were formed or they have since been eroded away (Quinn and Oliver, personal communication).

CONCLUSIONS

In Pennsylvanian time, as the movements associated with the Acadian Orogeny entered the waning stages, an area of high relief existed to the north, east, and northwest of the Narragansett Basin. The rocks of this upland area were probably a complex of folded and faulted metamorphic rocks together with minor intrusive masses of granitic types. Among the metamorphic rocks were quartzites and schists of Cambrian or Ordovician age. These could have been a continuation of beds of similar age in the Maritime Provinces of Canada. The main source area for the Pennsylvanian sediments may have existed where Massachusetts Bay is now located. From this northeastern source area mountain streams carried freshly eroded material into the Basin, depositing it in the form of broad alluvial fans; the Pondville Formation being a basal conglomerate in most places. Swamps along the floodplains of major rivers provided the necessary environment for the formation of coal and black shale. Simultaneously, red soils that formed in the north and northwest were being eroded and transported into the Basin where they colored the sediments of the Wamsutta Formation.

Following, and perhaps penecontemporaneously with the deposition of the Rhode Island and Wamsutta Formations an increase in stream competency produced the coarse Dighton and Purgatory conglomerates that now cap the underlying rocks. The presence of these coarse conglomerates in the highest stratigraphic position seems to imply that greater thicknesses of sediment once overlay these rocks and have since been removed. The post-depositional folding of the rocks probably took place as a phase of the Appalachian Orogeny and produced the present Narragansett Basin synclinorium.

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REFERENCES

CLOOS, H., 1938, Primäre richtungen in sedimenten der Rheinischen geosyncline: Geol. Rundschau, v. 29, p. 357–367.

CROWELL, J. C., 1955, Directional-current structures from the Prealpine Flysch, Switzerland: Geol. Soc. America Bull., v. 66, p. 1351–1384.

KAY, G. M., 1945, Paleogeographic and palinspastic maps: Am. Assoc. Petroleum Geologists Bull., v. 29, p. 426–450.

———, 1951, North American geosynclines: Geol. Soc. America Mem., no. 48, 143 p.

KING, P. B., 1948, Geology of southern Guadalupe mountains, Texas: U. S. Geol. Survey Prof. Paper 215, 183 p.

KNIGHT, S. H., 1929, The Fountain and Casper Formations of the Laramie Basin: Univ. Wyoming Publ. in Science, Geology, v. 1, 82 p.

KRUMBEIN, W. C. AND SLOSS, L. L., 1951, Stratigraphy and sedimentation. 1st ed., W. H. Freeman and Company, San Francisco, 497 p.

KRYNINE, P. D., 1950, Petrology, stratigraphy, and origin of the Triassic sedimentary rocks of Connecticut: Connecticut Geol. Nat. History Survey Bull., v. 73, p. 6–239.

KUENEN, PH. H. AND SANDERS, J. E., 1956, Sedimentation phenomena in Kulm and Flozleeres graywackes, Sauerland and Oberharz, Germany: Am. Jour. Sci., v. 259, p. 649–671.

MCKEE, E. D., 1955, Report on studies of stratification in modern sediments and in laboratory experiments: Office of Naval Research, Project Nonr 164 (00) NR 081 123, 61 p.

MCKEE, E. D. AND WEIR, G. W., 1953, Terminology for stratification and cross-stratification in sedimentary rocks: Geol. Soc. America Bull., v. 64, p. 381–390.

PAGE, A. W., 1930, The source of the pebbles in the Dighton Conglomerate: Unpublished master's thesis, Brown University, 43 p.

PERKINS, E. H., 1920, The origin of the Dighton Conglomerate of the Narragansett Basin of Massachusetts and Rhode Island: Am. Jour. Sci., 4th Ser., v. 49, p. 61–75.

PETTIJOHN, F. J., 1957a, Sedimentary rocks, 2nd ed., Harper and Brothers, New York, 718 p..

———, 1957b, Paleocurrents of Lake Superior Precambrian quartzites: Geol. Soc. America Bull., v. 68, p. 469–480.

QUINN, A. W., 1953, Bedrock geology of Rhode Island: New York Acad. Sci. Trans., Ser. 2, v. 15, p. 264–269.

QUINN, A. W. AND GLASS, H. D., 1958, Rank of coal and metamorphic grade of rocks of the Narragansett Basin of Rhode Island: Econ. Geology, v. 53, p. 563–576.

QUINN, A. W. AND SPRINGER, G. H., 1954, Bedrock geology of the Bristol quadrangle and vicinity, Rhode Island and Massachusetts: U.S. Geol. Survey, Geol. Quadrangle Map, no. GQ 42.

QUINN, A. W. AND OLIVER, W. A., JR., in press, Pennsylvanian of the United States-New England: Am. Assoc. Petroleum Geologists.

SHALER, N. S., WOODWORTH, J. B., AND FOERSTE, A., 1899, Geology of the Narragansett Basin: U.S. Geol. Survey Monograph 33, 402 pp.

VAN BURKALOW, A., 1945, Angle of repose and angle of sliding friction: An experimental study: Geol. Soc. America Bull., v. 56, p. 669–708.

VAN HOUTEN, F. B., 1948, Origin of red-banded Early Cenozoic deposits in the Rocky Mountain region: Am. Assoc. Petroleum Geologists Bull., v. 32, p. 2083–2126.

WALCOTT, C. D., 1898, Note on the brachiopod fauna of the quartzite pebbles of the Carboniferous conglomerates of the Narragansett Basin, Rhode Island: Am. Jour. Sci., 4th Ser., v. 156, p. 327–328.

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FIG. 1, DECEMBER, 1959

MINERALOGY AND PETROGRAPHY OF MARINE BOTTOM SEDIMENT SAMPLES OFF THE COAST OF PERU AND CHILE[1]

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ABSTRACT

The mineralogy and petrography of forty cores of marine bottom sediments from the Peru-Chile Trench area were studied by X-ray and microscopic techniques. Samples from each core were collected at intervals of 10 cm, or more frequently where visible lithologic variations occur. The $-1.3\,\mu$ fractions of many of these samples were also studied and the clay minerals identified by means of treatment with ethylene glycol and by heating to 200° and to 450°C.

The most common minerals in the cores are quartz, plagioclase, calcite, and the clay minerals kaolinite, chlorite, illite, and a mixed-layer clay predominantly montmorillonite. Halite and gypsum are important in many cores as results of dehydration of the cores. Volcanic glass, in various stages of devitrification, is extremely common in nearly all the cores; some samples are sufficiently abundant in glass to be called ash beds.

Among the less common minerals are aragonite, dolomite, rhodochrosite, potassic feldspar, glauconite, biotite, phillipsite, pyroxene, and amphibole. Chemically precipitated dolomite is found in one core at a water depth of 4600 meters. Besides dolomite, minerals which are at least partly authigenic are quartz, calcite, rhodochrosite, phillipsite, glauconite, and kaolinite. The observed mineral associations are given in a table.

The gross lithology of the cores includes sand, silt, mud, black mud, and calcareous and siliceous ooze. While large lithological variations exist between adjacent cores, within each core the lithology tends to be fairly uniform over the entire length.

The methods of identification of the 7–14 Å clay minerals are in an unsatisfactory state. The Bradley criteria are applicable to fine-grained, poorly crystalline chlorite, of relatively lower thermal stability than the well-crystallized chlorite to which the Brindley criteria apply. The very identification of a chlorite in a mineral mixture would thus be predicated on assumptions regarding the detailed nature of the material. The two sets of criteria, however, are not altogether contradictory; by a suitable combination it is possible in many cases not only to identify the chlorite but also to estimate its crystallinity. Most of the chlorites from the Peru-Chile Trench area satisfy the Bradley criteria.

Samples from the seaward side of the Peru-Chile Trench are uniformly fine mud. Samples from within the Trench are largely fine mud but include thin beds of silty to sandy material. Samples from the landward side of the Trench are heterogeneous in size as well as in mineralogical and chemical compositions. Although on the whole the near-shore samples tend to be most coarse-grained, there is no simple correlation between grain size and distance from the coast, nor between grain size and bottom topography. Sediment transport appears to be due largely to bottom currents, the existence of which is independently established by the discovery of graded bedding and cross-bedding in a number of the cores.

INTRODUCTION

During the winter months of 1955–1956, the research vessel *Atlantis*, of the Woods Hole Oceanographic Institution, under the joint leadership of B. Kummel, P. D. Trask, and the late H. C. Stetson, cruised the Pacific Ocean off the coast of Peru and northern Chile, covering the central part of the area of the Peru-Chile Trench. One of the principal objectives of the cruise was to collect bottom sediment samples from this tectonically active, but hitherto little studied area. Eighty-four Stetson type gravity cores, ranging in length from 1 foot to 8 feet, averaging about 5 feet, were collected from eight traverses. Seven of these traverses lie approximately at right angles to the shore line, spanning the Peru-Chile Trench; one traverse runs along the coast between Arica, Chile, and Callao, Peru.

The mineralogy of 14 of these cores has already been published (Zen, 1957); the present paper is a final report of this study, covering 26 other cores as well as some revisions and emendations of the earlier data. Although only about half of the cores in the

[1] Contribution no. 389 from the Department of Mineralogy and Petrography, Harvard University; no. 1036 from the Woods Hole Oceanographic Institution.
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[2] In the preliminary report (Zen, 1957) on this core, this mineral was not recognized. The following discussion corrects and supersedes that report.

collection have been examined, the attempted even distribution of the samples (fig. 1) and the nature of the results suggest that what is known may be fairly representative of the area as a whole.

The sediments from the Peru-Chile Trench area are of special interest for several reasons. The region is one of active tectonism and volcanic activity, and may well represent a typical eugeosynclinal belt of sedimentation. Much effort has gone into the study of ancient eugeosynclinal deposits, but more data from their supposed modern counterparts are desirable. The varied climatic conditions and source rocks on shore, coupled with the rugged land and submarine topography, as well as relative paucity of sediment data to date (Revelle, 1944, Ewing, Heezen, and Ericson, 1959, Worzel, 1959), make the study of the sediments in this region interesting.

For bed rock geology along the coastal region, the reader is referred to the works of Jenks (1946, 1956), Cristi (*in* Jenks, 1956), and Rüegg (1957). Unfortunately, hydrographic data on the coastal and near-shore waters are rather poor; Gunther's study (1936) of the surface hydrography is one published source. The bottom topography, on the other hand, has received some attention; a review of the literature was given by Zeigler, Athearn, and Small (1957), who also reported 14 bottom profiles across the Peru-Chile Trench from echo-sounding data collected by the *Atlantis* cruise, as well as data from the 1952 *Shellback* Expedition of the Scripps Institution of Oceanography. More recently, the *Downwind* Expedition of the Scripps Institution of Oceanography (Revelle, 1958) has further augmented the oceanographic and geologic data from the Peru-Chile Trench area.

METHOD OF STUDY

The sediment cores were stored in the plastic liners of the coring tubes plugged with cork or plastic stoppers. Despite the fact that they were stored in a high-humidity cabinet, many of the cores were partially or completely desiccated when opened for study. Because of original incomplete filling, and shrinkage during subsequent drying, some disturbance of the samples, before and during the opening of these cores, proved unavoidable. These are noted in the descriptive logs.

When a core was split open, the sediment was sliced longitudinally into two halves. The megascopic lithology was immediately logged and the approximate carbonate content tested with 6 N HCl. The core and log were photographed together. Samples were taken at roughly 10 cm intervals, or wherever a visible lithologic change occurs. The samples were air-dried for grinding and study.

The methods of preparation and study of both the bulk and the clay fractions of the samples, by X-ray and microscopic examinations, have been described elsewhere (Zen, 1957, 1959; Schmalz and Zen, in preparation). All X-ray work was done on a Norelco Geiger-counter diffractometer with Cu radiation and Ni filter. The clay-fractions were obtained by simple decantation of a suspension from standard cylinders at fixed time intervals, producing material with upper size limits whose effective settling diameter was calculated by Stokes' Law to be about 1.3 μ (Zen, 1959, p. 30). The clay-fractions were washed and dried on glass slides to produce maximum orientation of the platy minerals. Ethylene glycol was used for lattice expansion studies.

In a few instances, the existence of a mineral, such as rhodochrosite, is verified by X-ray fluorescence analysis, on a Norelco unit using LiF as analyzer.

The criteria used for the identification of various mineral phases have been discussed in earlier papers (Zen, 1957, 1959). Specific points requiring comment will be made under the sections on individual minerals.

DESCRIPTION OF THE CORES

The 40 cores studied include all seven traverses transverse to the Pacific coast, and are shown as solid circles in figure 1; the unopened cores are shown as open circles. The locations of the core stations were given by Zeigler and others (1957), who also discussed the probable errors due to navigational uncertainties. The depths of water, taken from the Scientist's Log Book of the cruise, are from echo soundings and have not been corrected for sound velocity in deep waters (see Zeigler and others, 1957, p. 240).

Not all of the samples have been specifi-

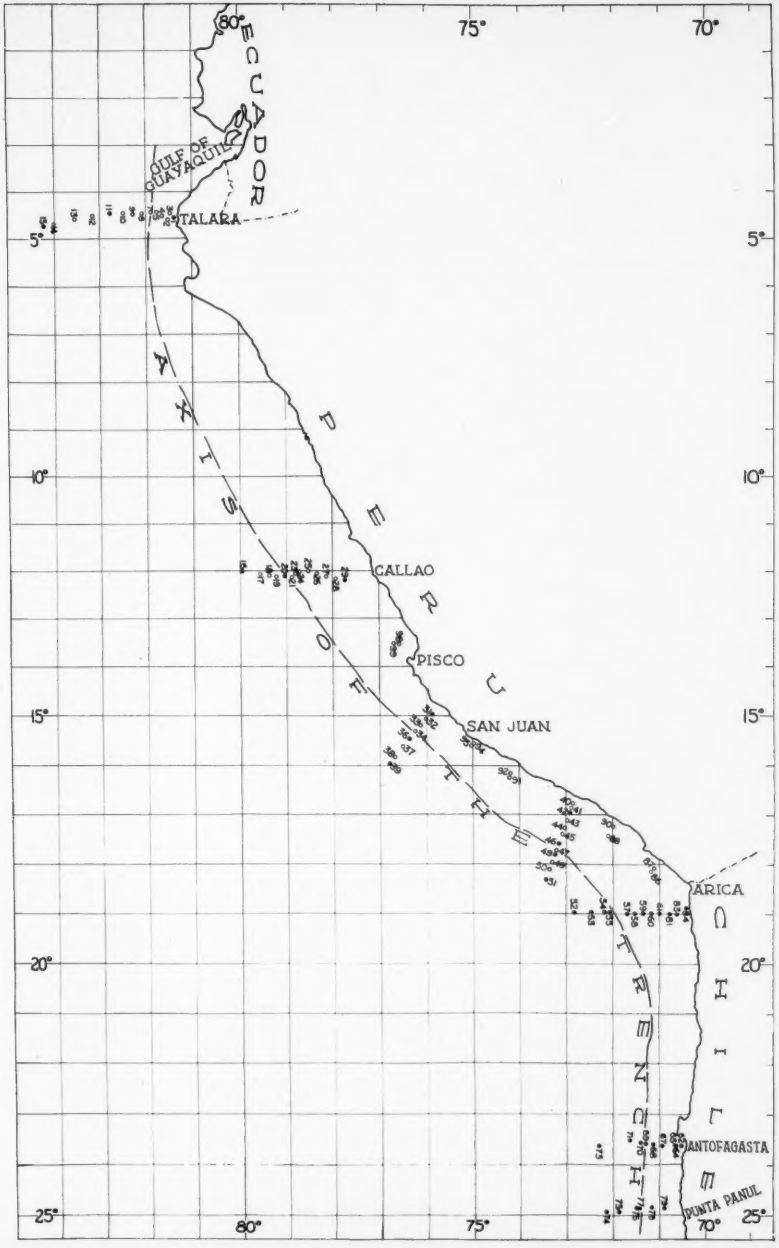

FIG. 1.—Map showing the location of the 84 cores. Solid circles: cores have been studied. Open circles: cores have not been studied.

cally studied for the clay mineralogy of the $-1.3\ \mu$ fraction. Instead, for each core the X-ray diffraction results of the bulk samples were examined; the sample that appeared most interesting and worthy of detailed study was then prepared for the $-1.3\ \mu$ fractions. Conclusions drawn on the clay mineralogy, based on bulk samples, accord with those drawn on the $-1.3\ \mu$ fractions so consistently, that for routine identification of the mineral groups (for example, montmorillonite, chlorite), the bulk sample appears adequate.

MINERALOGY

The detailed mineralogical data of the cores are presented in Table 1, and also in Table 2, where the mineralogy of each depth level corresponds to data from a single X-ray sample and therefore shows what minerals are actually found together. The individual minerals or mineral groups are considered below; considerations of their mutual relations, and possible implications on the environment of deposition or source material, will not be a subject of this paper.

Quartz

Quartz is an ubiquitous mineral in the cores studied, and is the single most abundant mineral in many of them. Its identification is relatively simple both by X-ray and by optical methods. In an oil immersion mount, however, much of the quartz can be seen to be angular fragments of apparently detrital origin, with no evidence for secondary overgrowth. Devitrification of volcanic glass in many of the samples also results in part in the formation of quartz. Quartz is rarely, if ever, found in the clay fraction of the samples with a maximum grain size of about $1.3\ \mu$

Plagioclase

Next to quartz, plagioclase feldspar is the most common mineral encountered in the cores. On the X-ray chart, its most intense line, at about 28° 2θ ($d = 3.2$ Å), commonly, though not invariably, shows multiple peaks. If laboratory data on high-temperature plagioclase may be used, this multiplicity of peaks indicates an anorthitic component in the plagioclase in excess of about 30 percent by weight (Smith, 1956, p. 52). However, this multiplicity of peaks may be simply due to the superposition of peaks from plagioclase grains of different compositions and different lattice spacings.

Under the microscope, the albite-twinned, angular fragments of plagioclase can be easily recognized. These grains commonly give at least one index of refraction greater than 1.56, which indicates that the plagioclase is rather calcic. Occasionally, euhedral plagioclase grains can be found embedded in fresh to nearly fresh volcanic glass; more commonly these grains are embedded in a fine-grained material which is presumably devitrified glass. Much of the plagioclase grains probably were derived from such an origin. The grains are commonly fresh, showing little or no sign of alteration.

It is uncertain if plagioclase forms as a product of devitrification. One would expect such plagioclase to be relatively soda-rich (albitic); and if untwinned and in a fine-grained mixture, such a mineral would be difficult to identify.

Potassic Feldspar

The identification of potassic feldspar is considerably less certain than that of plagioclase in the present study. This mineral has not been recognized optically, and its identification rests solely on the presence of the strongest potassic feldspar line at 27.5° 2θ; this peak is commonly of low intensity on the X-ray chart and may be interfered with by lines from other minerals, such as the (111) of halite and the (110) of rutile. Where the potassic feldspar line is definite on the chart, however, it generally occurs in more than one, and commonly consecutive, depth levels in a given core.

Because of the nature of the material, it has not been possible to determine the specific nature of the potassic feldspar phase —that is, its detailed composition and whether it is triclinic or monoclinic in symmetry. It is also unknown if the grains are of detrital or authigenic origin.

Pyroxene and Amphibole

Pyroxene and/or amphibole, predominantly the latter, are commonly identified in the cores. Microscopic examination shows these to be relatively coarse, angular grains,

(*Text continued on page 522*)

TABLE 1.—*Lithology and mineralogy of the cores*

Core No.	Water depth (meters)	Depth in core (cm)	Description
1-1	825	0–7	Empty
		7–30	Brown to gray silty mud, with visible mica flakes. Faint layering due to size difference at 1 mm intervals. Weak, spotty HCl reaction. Predominantly angular quartz and feldspar. Abundant siliceous microfossils and rare glass
		30–34	Rusty brown layer. Moderate HCl reaction
		34–90	Blue-gray mud with mica flakes and broken shells. Rusty brown along borders of core and along cracks. Moderate HCl reaction. Mineralogy like 7–30 cm levels
11-1	3200	0–10	Empty
		10–144	Fine, olive-green clayey mud. No layering. Rare white round spots ½ mm across. Moderate HCl reaction above 35 cm level; vigorous below. Quartz is important. Abundant devitrified glass, diminishing in amount downward. Siliceous and calcareous fossils are very abundant
15-1	4047	0–23	Empty
		23–201	Fine, soft, plastic clayey mud. Mostly olive-green, with areas about ½ mm × 3 mm of brown color, above 44 cm and below 178 cm levels. Center of core tends to be blue-green with gradual color boundary. White spots, 1 mm in size, scattered uniformly in core. Vigorous HCl reaction. Calcite is important; quartz and plagioclase are subsidiary and partly detrital. Siliceous and calcareous microfossils
16-2	4660	0–8	Empty
		8–10	Fine clayey mud, light brown. No HCl reaction. Quartz is important (same is true throughout the core)
		10–20	Mixed light brown and olive-green clayey mud. No HCl reaction. Siliceous microfossils
		20–78	Light olive-green to green-gray mud, with irregular layering due to deeper coloration about 2 mm thick below 53 cm level. No HCl reaction
		78–90	Same, but yellow-olive color with fairly sharp contact
		90–110	Same, grading back to olive-gray
		110–137	Olive-gray mud, with irregular layering due to color variation to pink-gray, dark gray, or yellow-gray; otherwise same. Devitrified glass
		137–153	Yellow-brown mud, otherwise the same. Faint 2 mm layers of gray color. Rare fresh glass
		153–169	Gray to bluish gray mud, otherwise the same
20-2	5630	0–8	Empty
		8–12	Medium brown sand in muddy matrix. No HCl reaction. Quartzofelcspathic, with devitrified glass and siliceous microfossils
		12–17	Alternating 1–5 mm layers of olive-gray vs. dark brown mud, with a few thin streaks of pale, clean sand. No HCl reaction
		17–20	Dull buff chalky-looking layer with sharp contacts. No HCl reaction
		20–70	Olive-gray, hard, dense, uniform, clayey mud, with thin irregular brown streaks and bands 1–5 mm wide. Rare white spots 1 mm across. Grades down to dark brown, then to brown-olive, gradually becoming silty below 65 cm level. No HCl reaction. Rare glass
		70–76	Dark olive-brown silt, moderate HCl reaction
		76–82	2 mm streaks of clean sand in silt. Vigorous HCl reaction
		82–90	Sandy silt grades down into hard brown mud. None to moderate HCl reaction. Fresh glass and calcareous and siliceous fossils
		90–98	Grades down to brown fine sand. Vigorous HCl reaction
		98–105	Dark brown silty mud with sharp upper contact. Slight color variations at 5 mm intervals suggesting layering. Pass downward to fine, friable sand. No HCl reaction
		105–113	Brown sand, partly in mud matrix. Sand is friable where matrix is absent. Vigorous HCl reaction
		113–115	Thin layers of muddy silt vs. friable sand
		115–121	Friable fine sand. Vigorous HCl reaction
		121–126	Brown clayey silt. Vigorous HCl reaction
29-2	1075	0–6	Olive-green, hard, compact, silty sand, massive and uniform, without stratification. Numerous white shell fragments. Moderate HCl reaction. Largely quartzofeldspathic with siliceous microfossils
		6–119	Hard, compact, massive silty sand, light buff-brown, with cleavage flakes of feldspar (?). Rare tiny white spots scattered in interval between 71–87 cm levels. Moderate HCl reaction. Rare glass
31-3	225	0–12	Empty
		12–17	Dark olive-brown, homogeneous clayey mud. Weak HCl reaction. Largely microfossils, showing no X-ray pattern and optically isotropic, throughout the core
		17–23	Grades down from above through light brown silt to white, friable, sandy layer (2 cm). No HCl reaction
		23–42	Sharp contact above; fine brown clayey mud. No HCl reaction
		42–48	Grading down into yellowish white sandy layer (2 cm), with irregular bodies of brown mud. No HCl reaction
		48–62	Sharp upper contact; brown mud with light-colored sandy layers 1 mm thick, locally crossbedded. No HCl reaction
		62–77	Brown clayey mud. No HCl reaction
		77–90	Alternation of 1 mm layers of brown clayey and pale sandy layers, with planar beddings. No HCl reaction
		90–107	Brown clayey mud with occasional shell remains. Weak HCl reaction. Abundant quartz at 97 cm level
		107–115	Like 77–90 cm levels, but strongly crossbedded. Weak HCl reaction
		115–174	Brown mud, with thin white layers at irregular intervals; the latter type becoming rarer towards the bottom. No HCl reaction except locally
		174–183	Like 77–90 cm levels. Weak to no HCl reaction

TABLE 1.—*Lithology and mineralogy of the cores (continued)*

Core No.	Water depth (meters)	Depth in core (cm)	Description
36-3	4435	0–199	Deep olive-brown, clayey mud. Uniform textured, without visible grains. Occasional irregular patches varying in color from pale brown to dark brown. Rare white ovoids scattered throughout the core. No reaction with HCl except in depth intervals between 45 and 120 cm. Largely quartz and feldspar, with common devitrified glass and abundant fossils
39-3	2600	0–30	Brown, friable silt with scattered white and black spots. Vigorous HCl reaction. Largely calcite (organic remains). Abundant glass throughout the core
		30–36	Grades down to white silty loam, with sharp contact at the bottom. Moderate to weak HCl reaction. Largely plagioclase
		36–63	Brown silt with interspersed layers of white chalky silt in the upper part; otherwise same as 0–30 cm. Sharp contact at the bottom changing to
		63–90	Pale, chalky silt, with vigorous HCl reaction, grading down to
		90–185	Pure white chalk, without stratification. Vigorous HCl reaction
42-4	1152	0–40	Unconsolidated, medium sand. Massive and homogeneous, dark olive-green. Rare 1 mm laminae of white sand. Vigorous HCl reaction except for the top 10 cm. Largely quartz and feldspar, with partially devitrified glass
		40–80	Gradationally changes from above into olive-yellow color with local brown stain; otherwise no change in lithology. Vigorous HCl reaction, in part due to aragonitic shell fragments
		80–86	Gradationally changes from above into light gray, fine silt with dark green partings. Vigorous HCl reaction
46-4	5515	0–194	Pale buff-gray, fine, hard, uniform clayey mud, without visible textural variations, and only very faint suggestion of layering due to shades of gray at 1 mm intervals, within the following depth intervals: 30–36 cm; 62–67 cm. HCl reaction: moderate, 0–20 cm; none, 20–90 cm; moderate, 90–100 cm; none, 100–115 cm; moderate, 115–194 cm. Rare rusty spots and wisps throughout the length of the core. Predominantly quartz and feldspar, with glass and siliceous fossils Note: Bottom stopper lost on receipt of core. Core is completely dry and portions have moved relative to one another during handling
48-4	6146	0–14	Sticky, fine clayey mud. mostly olive to brown, with local black layers. No HCl reaction. Predominantly quartz and plagioclase, with abundant glass and microfossils, throughout the core
		14–16	Light brown, friable layer with oölitic texture. No HCl reaction
		16–80	Same as 0–14 cm interval; below 32 cm level largely olive-brown with faint, irregular layering due to color variation. No HCl reaction
		80–82	Yellowish olive, silty clay. No HCl reaction
		82–151	Same as 16-80 cm interval. No HCl reaction
51-4	4456	0–18	Empty
		18–80	Deep brown, plastic clayey mud, uniform and homogeneous, nonstratified, with rare white, tiny ovoids. Gradually becomes brownish gray towards the bottom. No HCl reaction. Largely quartz and feldspar, with microfossils and rare glass throughout the core
		80–91	Same as above, except that the mud is hard and non-plastic
		91–254	Brown plastic mud as above, gradually becoming olive-brown below 200 cm level. Very local HCl reaction
52-5	4278	0–12	Empty
		12–31	Reddish chocolate-brown fine clayey mud. Homogeneous and uniform, slightly mottled with deeper color. At 25 cm level there is a 1 cm layer of sooty-gray color. No HCl reaction. Quartz and feldspar predominate in the core
		31–76	Olive yellow-brown fine mud. Homogeneous, with irregular and vague layering due to grayer patches. No HCl reaction
		76–120	Same, with irregular and indistinct greenish brown patches, 2 mm–10 mm; rarely suggesting layering. No HCl reaction
		120–231	Same as 31–76 cm interval
53-5	4597	0–6	Empty
		6–93	Brownish red, sticky, clayey mud, no stratification. Black and buff as well as white streaks. Color becomes yellowish brown below 13 cm level. No HCl reaction. Largely quartz and feldspar
		93–103	Same, with olive-green brown irregular streaks, about 2 mm thick, approximately normal to the length of the core. Also spots like in interval 103–109 cm below, between 93 and 95 cm levels. No HCl reaction except the spots
		103–109	Hunk of pale olive, hard, cement-like, much pitted material, surrounded by brown mud, which also contains smaller pieces of the same, some forming 1 cm oval-shaped coatings on mud. Poor HCl reaction on this object (which is dolomite), none on the mud
		109–200	Reddish brown, fine, sticky mud, no stratification or any textural variation. No HCl reaction
54-5	6011	0–6	Empty
		6–45	Brown, fine clayey mud, with numerous angular insets of pale buff to nearly white color, 1–2 mm across, in random orientation; locally voids exist in the space among the insets. Insets constitute about ⅓ of total bulk. No HCl reaction. Largely quartz in core
		45–66	Fine brown mud, massive, sticky and uniform. No HCl reaction
		66–82	Sharp contact with above, change to light yellow-brown mud. No textural change, but mud tends to crumble. No HCl reaction
		82–114	Buff brown mud with angular insets of pale color, generally 1 mm across but up to 3 mm, like between 6 and 45 cm levels. Patch of yellow, friable sand at 108 cm level. No HCl reaction
		114–119	Same as 82–114 cm levels, but with sooty black streaks
		119–162	Same as 82–114 cm levels; insets diminish in quantity downwards. No HCl reaction
		162–163	Layer of white angular "blocks," like inset material, up to 10 mm across. No HCl reaction. Largely material amorphous to X-ray
		163–178	Same as 119–162 cm levels, grading down to bright yellow mud, with white insets

TABLE 1.—*Lithology and mineralogy of the cores (continued)*

Core No.	Water depth (meters)	Depth in core (cm)	Description
55-5	6700	0–17	Empty
		17–58	Olive-gray medium sand (A), irregularly interlayered with olive-green silty clay mud (B). Sand is mostly quartz, but mica flakes may be seen. Poor to no HCl reaction, except where bulk of sample is B type. Largely quartz in core
		23	A
		28	A
		35–37	A plus B
		47–49	A plus B
		58–64	A, plus patches of B; sharp lower contact
		64–108	Same as 17–58 cm levels. B becomes dark olive towards bottom of section
		66–67	Finger of A
		78–79	A
		85–86	A
		91–92	A
		108–123	A and B in about equal amounts, in layers ½ cm to 2 cm thick, with sharp contacts
		123–125	Possible cross-bedding of A and B type of layers
		125–132	Same as 108–123 cm interval
		132–139	A and B mixed, no stratification
57-5	4106	0–60	Dull whitish green-gray mud, fine, compact, hard, with irregular thin films of a green color criss-crossing the sample at intervals of a few mms. No HCl reaction. Core is largely quartz and feldspar, with abundant glass partly devitrified, and microfossils
		60–62	Angular fragments of fine white silty matter in green argillaceous matrix. No HCl reaction
		62–118	Same as 0–60 cm levels
		118–138	Olive-brown, unconsolidated, well sorted sand with pale, argillaceous cement; sharp contacts. No HCl reaction
		138–175	Same as 62–118 cm levels
58-5	3110	0–13	Empty
		13–98	Olive drab, fine, massive silty mud, with rare visible grains of quartz (?). Rare white spots up to 2 mm across, and 2 mm fine, gray sand layers at 28 cm, 44 cm, and 46 cm levels. HCl reaction: none above 37 cm level, poor below 37 cm level; none on sand layers. Largely quartz and feldspar in core
		98–100	Gray, fine, well sorted medium sand, with sharp contacts on both sides. No HCl reaction
		100–129	Massive olive drab silty mud as above 98 cm level. No HCl reaction
		129–136	Faint color banding due to greenish vs. brownish olive layers at ½ mm apart. No HCl reaction
		136–155	Same as between 100 and 129 cm levels. No HCl reaction
		155–157	Well sorted sand with sharp contact, as between 98 and 100 cm levels. No HCl reaction
		157–187	Olive-brown fine silty mud as between 136 and 155 cm levels. No HCl reaction
		187–202	Same, but with whitish gray irregular and discontinuous layers 2 mm thick. No HCl reaction in mud, vigorous in white layers
59-5	2470	0–19	Empty
		19–31	Sticky, massive, dark olive brown clayey mud, with rare ½ mm white and buff spots. No HCl reaction. Largely quartz and feldspar in core
		31	1 mm layer of pale buff mud. Moderate HCl reaction
		31–77	Same as 19–31 cm interval, except with irregular streaks of buff and sooty black color approximating stratification. No HCl reaction
		77–166	Same massive mud, brown with dark charcoal brown streaks, but axial portion of the core is pale blue-brown. Abundant white spots between 77 and 84 cm levels. Moderate HCl reaction to 130 cm level, no HCl reaction below except for the white spots
		166–167	White, loamy, loose material with sharp contacts on both sides. No HCl reaction
		167–170	Same as between 77 and 166 cm interval
60-5	2268	0–11	Empty
		11–23	Light olive brown, slightly friable silty mud, with irregular stringers of lighter color about 1 mm. ×5 mm approximating layering. Rare white spots 1 mm across. No HCl reaction. Largely quartz and feldspar in core
		23–50	Same, becoming brown. Moderate HCl reaction
		50–58	Same, no HCl reaction
		58–73	Same, moderate HCl reaction
		73–95	Same, but pale stringers become more sharply defined as sharp, 1 mm beds at 1–5 mm intervals. Moderate HCl reaction
		95–129	Same, the two types of layers are dark brown vs. light olive brown in color, latter may not form continuous layers. Rare white spots. No HCl reaction except for the white spots
		129–143	Apparently same as above, but record disturbed due to loss of bottom stopper. No HCl reaction
61-5	1490	0–13	Empty
		13–40	Hard, massive green-gray siltstone. Rare visible cleavage flakes due to mica or feldspar. Rare white spots ½ mm across. No HCl reaction above 30 cm level, moderate to poor below. Largely quartz and feldspar in core
		40–120	Grade down to brown-gray and finer-grained; moderate HCl reaction above 80 cm level, poor to none below. Bright green, well-defined spots, about 2 mm across, at 103 cm level
		120–136	Gray-olive siltstone with faint layering due to color intensity variations, about 2 mm thick but uniform and persistent. HCl reaction: poor to none
81-5	1500	0–34	Olive-gray, massive, poorly sorted and loosely cemented medium sand, with rare reflecting cleavage flakes of mica or feldspar. No HCl reaction. Largely quartz and feldspar in core
		34–39	Friable sand, otherwise same as above
		39–40	Silty sand as above, but with crude parting into thin layers
		40–50	Same as 0–34 cm levels

TABLE 1.—*Lithology and mineralogy of the cores (continued)*

Core No.	Water depth (meters)	Depth in core (cm)	Description
83-5	1216	0–6	Empty
		6–108	Light olive-green fine silt, massive and uniform. Rare cleavage flakes of mica or feldspar. No HCl reaction on massive material; moderate on powdered material. Largely quartz and feldspar
84-5	933	0–76	Deep olive-brown, unconsolidated, non-clayey sand. Uniform, nonstratified. Scattered calcareous shell remains throughout. HCl reaction: moderate to weak. Largely quartz and feldspar in core, with abundant glass and microfossils
		76–156	Much like above, but with numerous small (about 2 mm×4 mm) irregular light-colored patches scattered in the core, locally concentrated to suggest layering. No HCl reaction
62-6	79	0–30	Massive, olive colored, well-sorted unconsolidated sand, grains about 0.5 mm across. Scattered shells of complete or fragmentary gastropods and pelecypods, locally concentrating into layers. Vigorous HCl reaction. Largely calcite and feldspar, with glass and abundant fossils (calcite and aragonite) in core
		30–90	Same as above but with dark brown argillaceous layers interspersed, up to 2 cm thick, at irregular intervals
		90–122	Same as above, but the sand becomes finer-grained approaching silt; core well stratified by color variation (coarser, olive color vs. finer, brown color)
64-6	228	0–36	Empty
		36–54	Dense, compact, dark olive-green, silty mud (type A). Strong odor. Above 42 cm level full of shell fragments. Mottled appearance due to 1 mm white spots. At 47 cm level there is a ½ mm light olive-yellow silt layer with sharp contacts. Poor HCl reaction. Largely quartz and feldspar, with siliceous microfossils and glass
		54–60	Grades down to light olive brown, about ⅓ of bulk is white, discontinuous layers ½ mm×3 mm, giving the core a ligniform texture (type B). Vigorous HCl reaction. Largely calcite, with siliceous microfossils
		60–66	Type A with sharp upper contact. Vigorous HCl reaction
		66–67	Type B
		67–81	Type A, with increasing proportion of type B towards the bottom
		81–84	Type A, with vigorous HCl reaction
		84–185	About 50% of bulk is largely continuous, sharply defined white fluffy layers like type B, less than 2 mm thick, interspersed in type A. Spacing of the former varies from 1 mm to 3 mm apart. Vigorous HCl reaction in Type A and poor to none in type B
		185–187	Type A only. Vigorous HCl reaction
		187–199	Same as between 84 and 185 cm interval. Vigorous HCl reaction
65-6	457	0–4	Empty
		4–72	Dark olive brown-gray, loose mixture of silt and sand. Silt has reflecting mica (?) flakes. About ⅓ to ½ of bulk consists of white, 1 mm "sand" grains, of foraminiferal tests. Massive, uniform; fossils are uniformly scattered in silt matrix. Rare 1 mm size gastropod shells. Vigorous HCl reaction. Largely calcite and feldspar in core
		72–119	Same, but color becomes paler brown olive except at 84–86 cm interval. Patches of fine silt at 79, 82, 84, 111, 113, and 116 cm levels. Vigorous HCl reaction
		119–135	Fairly rapid change downward to dark brown-gray color. Otherwise same as above. Vigorous HCl reaction
		135–147	Lighter color, otherwise same as above. Vigorous HCl reaction
		147–158	Darker and less friable than above, otherwise the same. Loose, light-colored patch at 152–154 cm interval. Vigorous HCl reaction
67-6	3036	0–18	Fine, homogeneous mud. Gray-tan on dry specimen. Some surface cracks have black coatings. Rare 1 mm white spots. No HCl reaction. Largely quartz and feldspar down to 58 cm level
		18–23	Dark gray-black sooty material, in granules 1 mm or less, mixed with mud granules of same size. No HCl reaction
		23–58	Same as 0–18 cm interval. No HCl reaction above 50 cm level; poor to moderate below.
		58–140	Same, color becomes pale tan. Vigorous HCl reaction. Largely quartz and calcite
68-6	5011	0–20	Buff, dense, dry mud with white spots less than 2 mm across, also irregular dark gray spots. No HCl reaction. Largely quartz and feldspar in core, with glass and siliceous microfossils
		20–23	Same, with dark brown to black coating along cracks. No HCl reaction
		23–24	Pellets of silty sand, 3 mm or less across, in brown mud matrix. No HCl reaction
		24–26	Same as 0–20 cm interval
		26–59	Homogeneous, buff-brown, somewhat friable silty mud, with reflecting cleavage flakes of some mineral. At 42 cm level there is a 2 mm layer of loose sand with sharp contacts. No HCl reaction
		59–77	Same, with irregular yellowish patches. No HCl reaction.
		77–92	White-buff mud with visible black specks and white spots. No HCl reaction
69-6	6950	0–12	Empty
		12–26	Hard, dense, buff-brown, dried clayey mud. Massive and homogeneous, with local patches of darker brown color. No HCl reaction. Largely quartz in core, with glass and siliceous microfossils
		26–34	Same, with vague 1–5 mm layering due to dark reddish brown color, with sharp but slightly irregular boundaries. No HCl reaction
		34–44	Same as 12-26 cm interval
		44–45	Yellow-buff, thin-bedded mud, bedding due to deep brown, ½ mm, sharp and planar layers. No HCl reaction
		46–177	Same as 34–44 cm interval; color gradually becoming olive gray below 80 cm level. No HCl reaction

TABLE 1.—*Lithology and mineralogy of the cores (continued)*

Core No.	Water depth (meters)	Depth in core (cm)	Description
70-6	6999	0–70	Fine, sticky, dark brown, homogeneous clayey mud with only occasional color variations to suggest layering. No HCl reaction. Largely quartz and feldspar in core, with variable amount of glass partly devitrified. Rare microfossils
		70–131	Gradual change from above: slowly becomes a clay-mud of steel gray color with the same texture. No HCl reaction
		131–134	Gray, friable, fine silt with gradational upper and sharp lower contacts. No HCl reaction
		134–138	Steel gray fine clayey mud as above 131 cm level. No HCl reaction
		138–141	Same as 131–134 cm interval with gradational upper and sharp lower contacts. No HCl reaction
		141–145	Olive gray-green clayey mud. No HCl reaction
71-6	5377	0–38	Empty
		38–96	Pale chocolate brown, fine, compact clayey mud, with stringers of gray color and patches of orange color. At 50, 58, and 70 cm levels there exist 1 mm layers of orange color below 3 mm layers of dark chocolate gray. No HCl reaction. Largely quartz and feldspar in core, with rare glass and with siliceous microfossils
		96–99	15 mm of friable orange mud with 2 mm of dark brown mud in the middle. Contacts sharp. No HCl reaction
		99–178	Deep chocolate brown, homogeneous and clayey mud. No HCl reaction
		178–182	Orange-brown friable mud, with gradual contacts. No HCl reaction. Largely quartz and rhodochrosite
		182–192	Same as 99–178 cm interval. No HCl reaction
73-6	4279	0–31	Empty
		31–107	Deep chocolate brown, sticky, clayey mud. Uniform and homogeneous, without stratification. Locally (67–72 cm) vaguely layered due to slight color differences, or motley-colored (78–88 cm). Color grades downwards into pale chocolate brown. No HCl reaction. Largely quartz in core, with glass and microfossils
		107–110	Yellowish brown silty mud, with sharp contacts. No HCl reaction
		110–279	Same as above 107 cm level, except that a 2 mm silty layer exists at 111 cm level. Color is predominantly chocolate brown near the top, grading downwards through yellow-brown to gray-brown. No HCl reaction
74-7	3968	0–98	Deep brown, fine, hard mud, with thin, faint layerings at 1–5 mm intervals due to color variations. HCl reaction: above 36 cm, none; 36–70 cm, moderate; 70–98 cm, none. Largely quartz and feldspar in core, with abundant glass and microfossils
		98–108	Same as above, with faint, irregular layers of buff mud. HCl reaction: moderate
		108–121	Same as 0–98 cm levels. HCl reaction: moderate
		121–141	Same as 98–108 cm levels. HCl reaction: moderate
		141–149	Same as 108–121 cm levels. HCl reaction: weak to none
		149–160	Same as 121–141 cm levels. HCl reaction: moderate to good
		160–173	Deep brown clayey mud with numerous fine, even layers of light buff mud. HCl reaction: vigorous
75-7	4700	0–23	Empty
		23–45	Chocolate brown, uniform, fine, compact clayey mud. Rare white spots scattered in core. No HCl reaction except the spots. Largely quartz and feldspar in core, with partly devitrified glass and siliceous microfossils
		45–64	Motley, pale chocolate vs. buff mud, otherwise same as above. Moderate to vigorous HCl reaction
		64–75	Buff, slightly loamy or chalky appearing mud with irregular upper contact. Vigorous HCl reaction
		75–127	Same as between 23 and 45 cm levels, with sharp upper contact. Irregular oval-shaped buff patches 1 cm across scattered in core. HCl reaction: none in chocolate brown mud, vigorous in buff patches
		127–140	Motley deep chocolate brown and pale chocolate patches, former occupying about ⅔ of the bulk. Rare white spots. Vigorous HCl reaction
		140–150	Same, with vague layering effect due to color contrast. Vigorous HCl reaction
		150–210	Same as 23–45 cm interval. Moderate HCl reaction above 187 cm level, none below
76-7	5669	0–6	Empty
		6–8	Dark brown mud, uniform and homogeneous (type A). No HCl reaction. Largely quartz and feldspar
		8–18	Same, with about equal amounts of irregular patches of fine, buff mud (type B); the two types in sharp contact. No HCl reaction. Largely feldspar and phillipsite
		18–30	Type A, with HCl reaction. Largely calcite
		30–35	Type B, with HCl reaction. Largely calcite with fresh glass
		35–40	Type A, with HCl reaction
		40–61	A and B in about equal amounts, forming layers or with B in irregular patches. HCl reaction
		61–70	Type A, with HCl reaction
		70–78	A and B in about equal amounts, with B in irregular patches. HCl reaction
		78–103	Type A, with HCl reaction. Largely feldspar and phillipsite
77-7	6218	0–13	Empty
		13–31	Pale purplish-tan mud, uniform in texture. Rare white spots. No HCl reaction. Largely quartz and feldspar in core, with siliceous microfossils and glass
		31–49	Same, becoming grayish white. No HCl reaction
		49–53	Irregular patches of dark gray sand with yellow sandy borders against buff-gray mud matrix. No HCl reaction
		53–96	Buff-gray mud as between 31 and 49 cm interval. No HCl reaction
		96–97	Dark gray loose sand, with yellow borders. No HCl reaction.
		97–164	Same as between 53 and 96 cm interval, with pockets of dark gray sand with yellow borders, at 139 cm level. No HCl reaction.

TABLE 1.—*Lithology and mineralogy of the cores (continued)*

Core No.	Water depth (meters)	Depth in core (cm)	Description
78-7	4042	0–10	Empty
		10–23	Buff-gray, massive and homogeneous silt. Moderate HCl reaction. Largely quartz and feldspar in core, with siliceous microfossils and partly devitrified glass
		23–24	3 mm layer of gray loose sand, with sharp lower and gradual upper contacts. Vigorou HCl reaction
		24–31	Buff olive, massive, muddy silt. Vigorous HCl reaction
		31–32	Gray loose sand
		32–90	Olive-gray, hard, massive and compact silt with mud matrix. Vigorous HCl reaction above 60 cm level, moderate between 60 and 85 cm levels, none below
		90	2 mm layer of loose sand
		90–106	Silty mud as between 32 and 90 cm interval, changing gradually to dense olive-brown clayey mud. Vague and irregular layering due to color intensity changes at 2–5 mm intervals. No HCl reaction
		106–150	Gradually becoming silty with visible reflecting specks of mineral grains. Dense, massive, olive-brown. No HCl reaction above 137 cm level, vigorous below
79-7	1856	0–2	Empty
		2–26	Olive-green, medium-fine, massive sand, with mud matrix. Local shell fragments. Vigorous HCl reaction. Quartz, feldspar and calcite dominate in core, with variable amounts of glass and microfossils
		26–30	Same as above, with 3–5 mm white sand layers at 3–5 mm distance apart.
		30–82	Same as 2–26 cm levels
		82–85	Gray unconsolidated, well-sorted sand, medium-coarse, without matrix material. Gradational upper, and sharp lower contacts. Fossils are chiefly foraminifera
		85–118	Fine brown clayey silt, uniform but for one pale, sandier layer between 94 and 96 cm levels. Visible quartz and mica grains rarely present
		118–131	Intimate interlayering of brown, muddy and white, sandy silt, grading down to uniform fine muddy silt
		131–138	Slightly coarser silt, same as above 118 cm level
		138–140	Same as between 82 and 85 cm levels; gradational upper and sharp lower contacts
		140–150	Same as above 138 cm level, with two thin sandy layers near the upper contact
		150–152	Same as between 138 and 140 cm levels; gradational upper and sharp lower contacts
		152–156	Same as above 150 cm level
		156–158	Same as between 150 and 152 cm levels; gradational upper contact

some of which are embedded in volcanic glass. It is probable that both these ferromagnesian minerals are completely derived from volcanic detritus. Part of the amphibole is dark brown and appears to be oxyhornblende.

Calcite

Calcite is a very common mineral in the cores. On the X-ray diffractometer, it is identified by the (10.4) reflection at 3.03 Å (29.5° 2θ); as a rule its presence is easily verified by optical examinations.

In many instances, the calcite can be definitely attributed to organic remains, either microfossils or fragments of larger forms; quite commonly, however, microscopic examination of the sample shows well-developed, discrete rhombs of calcite, or merely tiny highly-birefringent blebs. The origin of such material is much more in doubt. Finally, samples also exist which are identified as calcite on the basis of refractive indices but which are embedded in partly devitrified volcanic glass (Zen, 1959, p. 31). Such calcite is clearly inorganic and chemical in origin, formed during diagenesis.

The amounts of calcite in the cores are quite variable. In some samples, calcite occurs only as small, white, rounded spots in an otherwise calcite-free matrix. By and large, where it is the dominant mineral in a sample, the calcite can be definitely identified as organic in origin.

The detailed chemical composition of the calcite has not been studied in this survey work. Approximate X-ray data show that most of the calcite shows the (10.4) spacing very nearly that of pure $CaCO_3$.

There is no obvious correlation between the occurrence of calcite and other mineral phases in the samples studied.

Dolomite

Dolomite has been identified, in nearly all cases, by its X-ray diffraction pattern alone. A line at 2.89 Å (30.9° 2θ) is taken as indicative of dolomite. That the phase dolomite does in fact occur is demonstrated in two instances. In one, core 29-2, depth level 3 cm, a rhombohedral carbonate with $\omega \approx 1.67$ was found in an oil immersion mount and is taken to be the phase dolomite. A conclusive demonstration of dolo-

(*Text continued on page 531*)

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
1-1	7	x	x					x	x				x	x		
	16	x	x					x	x	x	x				x	
	25	x	x						x	x	x			x		
	35	x	x		?				x		x		x			
	47	x	x		x				x	x	x		x			
	56	x	x	?				x	x		x					
	64	x	x		x			x	x	x	x		x			
	73	x	x		x				x	x			x	x	x	
	82	x	x		x				x	x			x	x		
	90	x	x					x	x	x	x				x	
11-1	11	x	x						x	x					x	
	21	x	x		x				x	x	?		x			
	36	x	?		x				x	x	x					
	47	x	x		x				?	x	?		x			
	60	x	x		x				?	x	?					
	74	x	?		x				?	x	x					
	84	x	?		x				?	?						
	96	x	?		x					?						
	106	x	x		x					?						Olivine?
	116	x	x		x				x	x						
	128	x	x		x					?	?					
	139	x	x		x				x	x	x			x		
15-1	26	x	x		x					x	?				?	
	38	x	?		x				?	?						
	50	x			x					?						
	66	x			x											
	77	x			x											
	90	x	?		x					?				x		
	102	x			x											
	115	x			x				x		x					
	128	x	?		x				x	x						
	142	x	?		x					x						
	153	x			x				x							
	167	x			x											
	177	x	x		x				x	x	x					
	185	x			x							x		x		
	196	x	x		x				x	x			x			
16-2	9	x	x						x	x	x					
	18	x	x						x	x	x					
	32	x	x						x	x	x					
	44	x	x						x	x	x					
	55	x	x					x	x	x		?	?			
	68	x	x						x	x	x					
	79	x	x						x	x	x					
	90	x	x					x	x	x					x	
	101	x	x						x	x	x					
	113	x	x						x	x	x					
	125	x	x					x	x	?	x				?	
	135	x	x						?	x	x					
	140	x	x						x	x	?		x			
	149	x	x					x	?	x	?				x	
	160	x	x						x	x	x					
20-2	11	x	x					x	x			x			x	
	20	x	x		x			x	x	x	x					
	26	x	x					x	x	?	?	?	x			
	38	x	x						x	x	x				x	
	48	x	x						x	x	x					
	58	x	x					x	x	x		x		x		
	69	x	x		x			x	x	x	x			?	x	
	71	x	x		?			x	x	x		x				
	81	x	x		x			x	x		?			x		
	90	x	x		x			x	x	x	x			x	x	
	96	x	x		x			x	x		x			x		
	99	x	x					x	x	x	x	?	x			
	106	x	x					x	x		x				?	
	117	x	x		x			x	x	x		x		x		

[1] Abbreviations: Qt, quartz; Pl plagioclase; Ksp, potassic feldspar; Cal, calcite; Dol, dolomite; Arag, aragonite; Px, pyroxene; Amp, amphibole; Mu, illite; M.L., mixed-layer clay; Cl, chlorite; K, kaolinite; K-Cl, undifferentiated kaolinite and/or chlorite; Gyp, gypsum; Gl, glass.

x, mineral identified on bulk material; ?, identification is tentative; c, clay fraction mineralogy; s, several distinct phases present; s?, possibly several phases ;c?, tentative identification from clay-fraction study; *, one-layer montmorillonite.

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
29-2	3	x	x		x	x		x	x	?	x			x		
	13	x	x		x			x	x	x	x			x		
	23	x	x		x			x	x		x	x		x		
	38	x	x		x			x	x		?	x		x		
	49	x	x		x			x	x		x	?		x	x	
	62	x	x		?			x	x	?	x	?		x		
	73	x	x	x	x			x	x		x	?		x	x	
	80	x	x		x				x	?	?		x			
	93	x	x		x			x	x	x	?	x		x	x	
	105	x	x		x			x	x	x	?		x	x		
	114	x	x		x			x	x	x				x	x	
31-3	14	x	?		x				?					?		
	19	x	?	?	x				?					?		
	22	x		x	x				?		?			?		
	27	x	x					x	x		x					
	31	x		?	?									x		
	38	x		?												
	42	x	?	?	x				?					x		
	49	x		?	x									x		
	59	x			x									x		
	61	x			x			x	x		?			?	?	
	67	x	x													
	78	x								?		x		x		
	86	x			x					?		?		x		
	97	x	x						x	?	x					
	114	x			x											
	124	x	x						x		x			x		
	138	x	x					x	x		x					
	149	x	x					x	x		x			x	x	Rhodochrosite?
	162	x	x						x		x					
	174	x	x		x				?		?			?		
	181	x			x									x		
36-3	7	x	x						x	?	x					
	20	x	x		?				x	?	x				?	
	30	x	x						x	?			x			
	33	x	x					x	x	?	x			x		
	46	x	x					x	x	?	x					
	57	x	x		x				x		x			x	x	
	67	x	x						x	x	x					
	70	x	x		x			x	x	x	x			x		
	82	x	x		x				x	?	x			x		
	98	x	x		x				x	?	x			x		
	107	x	x		x			x	x	?	x					
	114	x	x		x			x	x	?	x				x	
	128	x	x					x	x	x	x					
	146	x	x		x				x	x	x					
	157	x	x						x	?	x			x		
	168	x	x					x	x	x	x			x	x	
	179	x	x		x		?	x	x	x	x					
	190	x	x						x	x	x				x	
39-3	4	x	x		x				x		x	x				
	12	x	x		x				x		?	x			x	
	16	x	x		x			x	x	x	x					
	22	x	x		x				x	x	?	x	x			
	27	x	x		x			x	x		x					
	31	x	x		?			x	x						x	
	37	x	x		x			x	x		?	x				
	39	x	x		x			x	x							Biotite?
	46	x	x		x				x		x					
	55	x	x		x				x							
	64	x	x		x			x	x							
	70	x			x										x	
	78	x	x		x				x	x	x					
	88	x	x	?	x				x	?			?			
	99				x											
	115				x											
	125	x		?	x											
	135	x			x						x					Hematite?
	150	x			x											
	162	x			x											
	172	x			x					?						
	185	x			x											

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
42-4	5	x	x		?			x	x		x				x	
	13	x	x		x			x	x				x		x	
	14	x	x					x	x			?	x		x	
	20	x	x		x			x	x		?		x		x	
	30	x	x		x			x	x				x		x	
	41	x	x		x			x	x			?	x		x	
	48	x	x		x			x	x		?		x		x	
	57	x	x		x			x	x				x	x	x	
	66	x	x		x			x	x				x		x	
	76	x	x		x			x	x		?		x		x	
	84	x	x		x			x	x			?		x	x	
46-4	1	x	x					x	xc	xcs	xc	xc	x	x	x	
	19	x	x					x	x	x	x	x				
	30	x	x						x		x	x				
	40	x	x						xc	xcs	xc	xc			x	
	52	x	x						x		?	x				
	64	x	x						xc	xcs	xc	xc			x	
	75	x	x						x	x	x	?				
	90	x	x						x		x	?				
	108	x	x		x			x	xc	xcs	xc	xc				
	124	x	x		x			x	x	x	x	?				
	140	x	x						x	x	x	?				
	153	x	x		?	?			x	x		x				
	166	x	x		?			x	x	x	?				x	
	179	x	x					x	x	x	?	x				
	190	x	x		?			x	xc	xcs	xc	c			x	Biotite
48-4	1	x	x					x	x		x				x	Biotite
	5	x	x					x	x		x				x	
	8	x	x					?	x	x	x				?	
	11	x	x					x	x	x	x				x	
	14	x	x					x	x		x				x	
	21	x	x					x	x	x	?	x			x	
	32	x	x					x	x	x	x	?	x			
	43	x	x					x	x	x	x			x		
	56	x	x					x	x	x	x	?	x			
	69	x	x						x		x					
	81	x	x						x	x	x			x		
	90	x	x						x	x	x					
	100	x	x						x		?	?	x			
	112	x	x		?				x		x				x	
	128	x	x					x	x		x	x	x		x	
	139	x	x						x		x					
	150	x	x						x		x	?	x			
51-4	18	x	x						x	x	x			x		
	30	x	x						x	x	x			x		
	42	x	x					x	x	x	x					
	56	x	x						x	x	x					
	62	x	x						x	x	x					
	80	x	x					x	x	x	x					
	96	x	x					x	x	x	x					
	105	x	x						x	x	?	x				
	119	x	x					x	x	x	x				x	
	130	x	x						x	x	x					
	145	x	x					x		x						
	158	x	x					x	x	x	x					
	175	x	x						x	?	x				x	Biotite?
	187	x	x						x	x	x	?				
	200	x	x						x	x						
	212	x	x							x						
	225	x	x						x	x						
	240	x	x						x	x	x					Olivine?
	253	x	x						x	x	?	x				
52-5	14	x	x						x	x			x			
	24	x	x						xc	xc	xc	xc				
	36	x	x						x	x			x			
	50	x	x						x	x	x	?	x			
	53	x	x						x	x			x			
	75	x	x						xc	xc	xc	?	x	x		
	90	x	x						x	x	x	?	x			
	107	x	x						x	x			x			
	119	x	x						x	x			x			
	130	x	x					x	xc	xc	xc	?	x			
	145	x	x						x	x			x			
	161	x	x						x	x			x			
	176	x	x						xc	xc	?	c	x			
	192	x	x						x	x			x	x		
	208	x	x						x	x	x		x			
	219	x	x						x	x			x			
	231	x	x						xc	xc	c	?				

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
53-5 (X-ray only)	7	x	x						xc	xc	xc	c	x			
	26	x	x	x					xc	xc	?	xc				
	41	x	x	x					x	x	x		x			Phillipsite?
	59	x	x						x		x					
	70	x	x					x	xc	xcs?	c	c				Phillipsite
	81	x	x						x	x		?				
	96	x	x						x	x	x					
	106	x	x			x		x	xc	cs?	xc	c				
	120	x	x						xc	xc	c	xc				
	133	x	x					x	x	x	?	x				
	146	x	x						x	x	?	x				
	155	x	x						xc	xc	xc	xc				
	171	x	x						x	x	x					
	188	x	x						x	x	x	?				
	199	x	x						x	x	x	?				
54-5 (X-ray only)	8	x	x						xc	xc	xc	xc				
	18	x	x					x	x	x	x	?				
	32	x	x					x	xc	xcs	xc	xc				
	42	x	x							x	x					
	50	x	x						xc	xc	c	xc				
	65	x	x						x	x	x	x				
	73	x	x						xc	xcs	xc	c				
	83	x	x						xc	xc	xc	c				
	86-88	x							?							
	94	x	x						xc	xc	c	c				
	108	x	x						x	x	?	x				
	114	x	x						xc	xcs	xc	c				
	126	x	x						x	x	x	?				
	136	x	x						x	x	x					
	149	x	x						x	xs	x	?				
	162	x														
	169	x	x						x	x	x					
	177	x	x						xc	xcs	c	xc				
55-5 (X-ray only)	23	x	x	?					xc	xcs	xc	c				
	32	x	x						x	x	x	?		x		
	45	x	x						x	x	x	?				
	55	x	x					x	xc	xcs	xc	c				
	63	x	x					x	x	x	?	x		x		
	77	x	x						xc	c	c?	c				
	89	x	x						x	x	x	?				
	99	x	x					x	x	x	x	?				
	105	x	x					x	xc	xcs	xc	c				
	115	x	x					x	x		x					
	130	x	x					x	xc	xc	xc	c				
	138	x	x	?				x	x	xs	x					
57-5	4	x	x						x	x			x	x		
	18	x	x					x	x	x	x				x	
	27	x	x						x	x	x	?	x	?		
	38	x	x						x	?	x			x		
	49	x	x					x	x	x	x					
	60	x	x						x		x				x	
	74	x	x						x		x					
	85	x	x						x	x	x	?		x		
	95	x	x					x	x	x	x			x	?	
	104	x	x					x	x	?	x					
	116	x	x						x	?	x	?	x	x		
	121	x	x					x	x		x			x		
	137	x	x					x			x			x		
	138	x	x						?	x	x			?	x	
	139	x	x						x	x	x				?	
	148	x	x						x		x	?				
	157	x	x						x		x			?		
	165	x	x					?	x		x				x	
	175	x	x						x	?	x					
58-5 (X-ray only)	16	x	x					x	x	x	?	x				
	36	x	x						x	x	?	x				
	53	x	x					x	x	x	?	x				
	65	x	x					x	x	x	?	x				
	76	x	x						x	xs	?	x				
	91	x	x						x	x	?	x		x		
	100	x	x					x	x	x	?	?		x		
	110	x	x						x	x	?	x		x		
	125	x	x					x	x	x	?	x				
	136	x	x						x	x	x	x				
	149	x	x					x	x	x	?	x				
	163	x	x						x	x	?	x				
	176	x	x						x	x	x	x				
	188	x	x						x	x	?	x		x		
	197	x	x						x	x	?	x		x		

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
59-5	25	x	x		x				x		x					x*
(X-ray	36	x	x	?					x	x	x					
only)	49	x	x					x	x	x	x					
	61	x	x						xc	xc	xc	c				
	72	x	x					x	x	x	x					
	82	x	x		x				xc	xc	c?	xc				
	93	x	x		x				xc	xc	xc	xc				
	110	x	x		x				x	x	x	x				
	120	x	x		x				xc	xc	c?	c	x			
	132	x	x					x	xc	xcs?	c?	xc				
	142	x	x						xc	xc	c	xc				
	153	x	x						x	x	x	x				
	161	x	x					x	x	x	x					
	167	x	x				?	?		x						
	169	x	x						x	x	x					
60-5	12	x	x						xc	xc	xc	xc		x		
(X-ray	28	x	x		x			x	x	x	?	x				
only)	36	x	x		x				x	x	?	x				
	49	x	x					x	x	x	x	?				
	57	x	x	?					x	x	x	?				
	71	x	x		x				xc	xc	xc?	c				
	80	x	x		x			x	xc	xc	xc	c				
	93	x	x		x				x	x	?	x				
	109	x	x						xc	xc	xc	c				
	120	x	x						xc	xc	c	xc				
	131	x	x					x	x	x	x	?		x		
	142	x	x	?				x	x	x	x	?				
61-5	14	x	x				?		x	x	x	x				
(X-ray	26	x	x					x	x	x	?	x				
only)	35	x	x		x			x	x	x	x	x				
	48	x	x		x				x	x	?	x				
	62	x	x		x			x	x	x	?	x				
	71	x	x		x				x	x	?	x				
	86	x	x		x				x	x	?	x				
	95	x	x						x	x	x	x				
	103	x	?						?	?						Glauconite
	108	x	x		x				x	x	?	x				
	121	x	x		x			x	x	x	x	x				
	133	x	x						x	x	?	x		x		
81-5	1	x	x					x	x	x	?	x		x		
(X-ray	11	x	x			?		x	x	x	?	x				
only)	22	x	x					x	x	x	?	x				
	35	x	x					x	x	?	x	x				
	46	x	x					x	x	x	?	x		x		
83-5	6	x	x					?	x	x	x	x				
(X-ray	17	x	x						x	x	?	x		x		
only)	28	x	x		x			x	x	x	?	x		x		
	40	x	x		x			x	?	x	?	x		x		
	49	x	x	?	x				x	x	?	x				
	60	x	x		x			x	x	x	?	x				
	72	x	x		x				?	x	x	x		x		
	80	x	x		x				x	x	?	x				
	92	x	x		x				x	x	?	x		x		
	106	x	x		x			x	x	x	x	x		x		
84-5	10	x	x					x	?	x	?	?	x	x		
	20	x	x		x	?		x	x	x	x	?	x		x	
	32	x	x		?	?			x	x	x			x		
	41	x	x		?			x	x	x	?	x		x		
	51	x	x					x	?	x	x	?		x	x	
	58	x	x		x			x	x	x	x	?		x		
	71	x	x		?				x		?	x		x		
	80	x	x		x			x	x	?	x	?		x	x	
	91	x	x					x	x	x	x	?		x		
	104	x	x		x				x	x	x	?		x	x	
	117	x	x		x			x	x	x	x	?		x		
	130	x	x		x			x	x	x	x	?		x	x	
	142	x	x		x			x	x	x				x		
	155	x	x						x		x	?		x	x	

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
62-6	2	x			x		x	x		?				x		
	11	x	x		x		x	x		?	x				x	
	21	x	x		x		x	x			x	?	x	x		
	31	x	x	?	x		?	x			?	x		x	?	
	40	x	x	x			x	x			x			x		
	49	x	x		x		x	x	x			x			x	
	60	x	x		x		x	x	x					x		
	68	x	x		x		x	x						?		
	79	x	x		x		x	x								
	90	x	x		x		x	x	x		x					
	101	x	x		x		x	x				x		x		
	110	x	x		x		x			?	x					
	121	x	x		x		x	x						x	?	
64-6	39	x	x					x	x	x	x			x	x	
	49	x	x		x			x	x		x					
	59	x			x			x	x		x	?				
	71	x	x		x			x	xc	c?	c?	c?				
	82	x	x		x			x	x	?	x	x				
	93	x	x		x			x			x	?	x			
	107	x	x			x	x	x	x		c?	x				
	104–112, dark	x	x		x	x	x	x	x		?	?	x		x	
	104–112, white	x	x		x	?	x	x		x			x			
	125	x	x		x	?	x	x	x		x			x		
	140	x	x		x	?	x	x	x	?	c?	c?		x		
	156	x	x		x	?	x		?	?	?	x				
	171 white	x	x		x	?	?	x								
	186 dark	x	x		x	?	?	x	xc	c?	c?	c?				
	196	x	x		x	?	x	x	x	?	?	x		x		
65-6 (X-ray only)	3	x	x		x			x	x	?	x	x				
	20	x	?		x			x	x	?	?	x				
	39	x	x		x		?	x	x	?	x	x				
	55	x	x		x			x	x		?	x				
	70	x	x		x			x	x	?	?	x				
	88	x	x		x			x	x	?	?	?				
	99	x	x		x			x	x	?	x	x		x		
	113	x	x		x			x	x	x	?	x				
	131	x	x		x			x	x	x	x	x		x		
	145	x	x		x	?		x	x		?	x				
	157	x	x		x			x	x	x	?	x		x		
67-6 (X-ray only)	1	x	x		?			x	xc	xc	xc	c?				
	10	x	x	?				x	x	x	x	?				
	22	x	x					x	x	x	x	?				
	36	x	x						xc	xc	xc	c?				
	49	x	x	?				x	xc	xc	xc	c?				
	64	x	x		x			x	x	x	x	?				
	79	x	x		x			x	x	x	x	?				
	89	x	x		x			x	xc	xc	xc	c?				
	105	x	x		x			x	x		x	x				
	116	x	x		x			x	x	x	x	x				
	127	x	x		x			x	xc	xc	xc	xc				
	139	x	x		x			x	x	x	x	?				
68-6	2	x	x					x	xc	xc	c	c?			x	Iron oxide?
	13	x	x					x	x	x	x	x				
	22	x	x					x	xc	xc	xc	xc				
	29	x	x					x	x	x		x				
	40	x	x					x	x	x	?	x				
	50	x	x		?			x	xc	xc	c	c?			x	
	60	x	x					x	x	x	?	x				
	71	x	x					x	xc	xc	xc	c?			x	
	81	x	x					x	x	x	?	x				
	91	x	x						xc	xc	c	c?			x	
69-6	14	x	x					x	x	x	x	x				
	28	x	x					x	xc	xc	xc	xc			x	
	40	x	x					x	x	x	x	?				
	45	x	x						xc	xc	xc	c?				
	56	x	x					x	xc	xc	xc	xc				Hematite?
	72	x	x					x	x	x	x	x				
	88	x	x					x	x	x	x	x				
	100	x	x					x	x	x	x	x			x	
	111	x	x					x	x	x	x	x				
	127	x	x					x	xc	xcs?	xc	xc				
	141	x	x					x	x	x	x	x			x	
	159	x	x					x	xc	xc	xc	xc				
	166	x	x						x	x	x	x			x	

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	Px-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Gl	Others
70-6	9	x	x					x	xc	xc	c?	c?				
	16	x	x					x	xc	c?	xc	c?				
	29	x	x					x	x	x	x	x				Biotite Hematite?
	41	x	x					x	x	x	x	?				
	52	x	x					x	x	x	?	x	x			
	65	x	x					x	x	xc	x	c?				
	75	x	x					x	x	x	x	?			x	
	89	x	x					x	x	x	x	?				
	100	x	x					x	x	x	x	?				
	111	x	x					x	x	x	x	x			x	
	121	x	x					x	x		x	?				
	129	x	x					x	x	?	x					
	132	x	x					x	x	x	x	?			x	
	137	x	x						x	?	x	?				
	140	x	x		?			x	x		x	x			x	Biotite
	144	x	x						x		x	?			?	
71-6	38	x	x					x	x	x	x	x			x	
	50	x	x					x	x	x	?	x				
	73	x	x					x	xc	xc	xc	c?			x	
	80	x	x						x	x	?	x				
	92	x	x						x	x	x	x				
	98	x	x						c	xc	c	c	x	x		
	113	x	x					x		x	x	?				
	126	x	x					x	xc	xc	c	c?				
	138	x	x						x	x	?	x				
	150	x	x					x	xc	xc	c	c?			x	
	164	x	x					x	x	x	?	x				
	175	x	x						x	x	x	?	x			
	179	x	x						x	x	?	?				
	180	x	x						x	x	x	x	x		x	Rhodochrosite
	182	x	x					x	xc	c	c	c?	x			
	191	x	x						x	x	x	?			x	
73-6	37	x	x					x	x	?	x	x			x	
	51	x	x						x	x	x	?				
	69	x	x						xc	xc	xc	c				
	77	x	x						x	x	x				x	
	87	x	x						x	x	x					
	99	x	x					x	x	x	?	x				
	109	x	x						x	?	x	?			x	
	113	x	x						xc	xc	xc	c			x	Biotite
	125	x	x						x	?	x	?				
	140	x	x						x	x	x	?			x	
	150	x	x					?	x	x	x	?				
	165	x	x					x	xc	xc	c?	c				
	178	x	x					x	x	x	x	?				
	190	x	x						x	x	?	x				
	205	x	x						x	x	?	?	x			
	215	x	x					x	x	?	?	x				
	229	x	x					x	x	x	x	?			x	Olivine?
	240	x	x						x	x	x	?				
	251	x	x							x	x					
	264	x	x					x	x		x	?				
	279	x	x					x	x	x	x	?	x			
74-7	2–4	x	x		x			x	x	x	?		x		x	
	10–11	x	x		x			x	x	x	?		x	x	x	
	15–16	x	x						x	x	x	?		x		
	19–20	x	x					x	x	xs	?	?	x			
	22–23	x	x					x	x	?	x	?	x			
	39	x	x		x				x	?					x	
	48–51	x	x		x			x	x	x	x	?	x		x	
	59–61	x	x		x			x	x	x	x	?	x		x	
	70–72	x	x		x				x	x			x			
	87	x	x		x			x	x	x	x	?	x		x	
	103	x	x		x				x	?	x	?				
	139	x	x		x			x	x		x	?			x	
	141	x	x	x					x	x	x	?				
	158	x	x	?	x			x	x	x	x	?			x	
	171–173	x	x		x				x		x				x	

TABLE 2.—*Microscopic and X-ray mineralogy of individual sediment samples (continued)*

Core no.	Depth in core (cm)	Minerals[1]														
		Qt	Pl	Ksp	Cal	Dol	Arag	ix-Amp	Mu	M.L.	Cl	K	K-Cl	Gyp	Cl	Others
75-7	24	x	x					x	xc	xc	xc	c?			x	Epidote?
	25	x	x		x				x	x		x				
	49	x	x		x			x	x	x		x			x	Hematite?
	61	x	x		x				xc	xc	c?	c?				
	71	x	x		x			x	x	?		x			x	
	81	x	x		x				x	x		x				
	92	x	x					x		x		x				
	101	x	x						xc	xc	c?	xc			x	
	115	x	x						x	x		x				
	127	x	x		x			x	x	x	?	x			x	
	137	x	x		x			x		x		x				
	145	x	x		x			x	x	x		x			x	
	158	x	x						x	x	?	x				
	170	x	x		x			x		x	?	x				
	178	x	x		x			x	x	x		x			x	
	190	x	x		x			x	x	x		x				
	205	x	x					x	xc	c?	c?	xc			x	
76-7	8	x	x	x				x	xc	xc	xc	c?			x	Phillipsite
	17	x	x	?	?				x		x	?	x		x	Phillipsite
	25	x	x	?	x				c	c?			x			
	31	x	x		x				x	?	x	?			x	Phillipsite?
	39	x	x	?	x								x			
	50	x	x	x	x					x			x			Phillipsite
	61	x	x	x	x				x	x			x			
	81	x	x	x	x				x				x		x	
	90	x	x	x	x				x	x	x	x				
	100	x	x	x					x				?		x	Phillipsite
77-7	15	x	x					x	xc	xc	xc	c?			x	
	28	x	x					x	x	x	?	x		x		
	34	x	x					x	x	x	?	x				
	48	x	x					x	x	x	x	x			?	
	51	x	x					x	xc	xcs	c	c?		x		Zoisite?
	62	x	x					x	x	x	x	x				
	76	x	x					x	x	x	x	x				
	90	x	x					x	xc	xc	xc	xc				
	102	x	x					x	x	x	?	x				
	113	x	x						xc	xc	xc	c?				
	125	x	x					x	x	x	x	x			x	
	137	x	x						x	x	x	x				
	149	x	x						x	x	?	x				
	161	x	x					x	xc	xc	xc	c			x	Phillipsite?
78-7	11	x	x					x	xc	xc	xc	c?			x	
	20	x	x		x			x	xc	xc	xc	c?			x	
	24	x	x		x			x	x	x	x	x				
	32	x	x		x			x	x	x	x	x				
	46	x	x		x			x	x	x	x	x				
	57	x	x		x			x	x	x	x	x				
	70	x	x		x			x	xc	xc	c?	xc			x	
	82	x	x		x			x	x	x	x	?				
	92	x	x		?				xc	c	xc	xc			x	
	102	x	x					x	x	x	x	?				
	116	x	x					x	x	x	x	?				
	127	x	x					x	x	x	x	?				
	138	x	x		x			x	xc	xc	xc	c?			x	
	150	x	x		x			x	x	x	x	?				
79-7	3	x	x		x			x	xc	c	xc	c				
	17	x	x		x			x	x		x	?			x	
	27	x	x		x			x	x	x	x	?				
	38	x	x		x				x	x	?	?	x			
	53	x	x	?	x				x	x	x	x			x	Olivine?
	63	x	x		x			x	xc	xc	xc	c				
	68	x	x	?	x				x		x	x				
	80	x	x	?	x			x	x	x	?	x			x	
	84	x	x	?	x			x	x	?	?	x				
	90	x	x		x			x	x		?	x				
	102	x	x		x				x	x	x	?			x	
	112	x	x		x			x	x		?	x				
	120	x	x		x				x		x	x				
	129	x	x	?	x				x		x	x				
	133	x	x		x			x	xc	c	c	c?			x	
	139	x	x		x			x		x	x	?				
	147	x	x		x			?	x		x	?				
	156	x	x		x			x	x		?			x	x	

mite, however, is in core 53-5. At depth levels between 104 and 108 cms, the core consists of a single, pitted chunk of olive-gray, cement-like material that reacts weakly with 6 N HCl. At adjacent levels smaller pieces of similar material are found, at least part of which form fragile coatings, 1 mm thick, on the clayey mud which constitutes the bulk of the core. On the X-ray chart the carbonate gives unmistakable dolomite pattern; unfortunately, due to the presence of other phases it has not been possible to decide whether the dolomite is ordered or disordered "protodolomite" (Graf and Goldsmith, 1956, p. 184). The mineral association of this particular occurrence of dolomite is given in table 2. Aside from quartz and plagioclase, clay-fraction studies show the presence of illite, kaolinite, chlorite, and mixed-layer clay. An amphibole has also been found.

Aragonite

Aragonite has been found in a number of cores, exclusively on the basis of X-ray studies. Aragonite is always subsidiary in amount, and occurs only where abundant organic carbonate fragments obtain.

In general, for a given core at a given depth level, only one carbonate phase exists. Cores 62-6 and 64-6 are the salient exceptions. Core 62-6 has both calcite and aragonite, whereas 64-6 has, in addition, dolomite throughout most of its length. The problem of chemical equilibrium among the carbonates in the open ocean has been discussed elsewhere (Zen, in press); the prevalent one-carbonate mineral associations are consistent with, though by no means confirm, the hypothesis of the attainment of chemical equilibrium among the carbonates. However, aragonite is known to be metastable under surface conditions (Jamieson, 1953; MacDonald, 1956; Clark, 1957) and must be excluded in any equilibrium considerations.

Rhodochrosite

Rhodochrosite, the manganese carbonate, has been observed about the 180 cm level of core 71-6. It occurs in a layer about 4 cm thick. The bulk material is orange-brown in color, loamy and incohesive, and passes both upwards and downwards into the chocolate-brown clayey mud typical of the core. Rhodochrosite is recognized under the microscope by its index of refraction and high birefringence. Many crystals appear to be skeletal and subhedral.

The strong reflections at 24.3° 2θ (relative intensity 50) and 31.3° 2θ (relative intensity 100), corresponding to d-spacings of 3.66 Å and 2.86 Å, respectively, agree with the data for rhodochrosite (Brindley, ed., 1958, A.S.T.M. card no. 7-268). The value of ω, 1.76 ± 0.005, is too low for rhodochrosite; however, this value might be low due to difficulties in measuring the very fine-grained material. X-ray fluorescence analysis of the sample, using LiF analyzer, yields a strong $Mn_{K\alpha_1}$ line at 62.9° 2θ.

The mineral association of the rhodochrosite-bearing layer is given in table 2; this consists of quartz, plagioclase, illite, kaolinite, chlorite, and mixed-layer clay dominantly montmorillonite. Clay-fraction studies on a sample from the 182 cm level, of similar material, yield these same clay minerals except possibly kaolinite. Optical examination of the sample shows the presence of volcanic glass.

Phillipsite

A mineral identified as phillipsite is found definitely in cores no. 76–7,[2] 53-5, and possibly in 77-7. The identification is based primarily on the X-ray diffraction pattern, with strong reflections at 7.14 Å and 4.10 Å (12.4° and 21.7° 2θ, respectively). The strongest reflection at 3.20 Å, corresponding to a 2θ value of 27.9°, unfortunately, interferes with plagioclase lines and is not useful. Table 3 gives a typical X-ray chart reading of a sample which contains much phillipsite.

Where identification is reported as "definite," the mineral has been verified by optical examination. In a typical sample, core 76–7, depth level 100 cm, phillipsite occurs as small, colorless, rectangular, euhedral, and untwinned crystals that are length-slow with $Z \wedge C \approx 29°$. The birefringence is very low, and $\beta \approx \gamma = 1.498 \pm 0.00$. According to Winchell and Winchell (1951, p. 343), this corresponds to a rather high calcium, therefore low-silica composition.

In some samples phillipsite is strongly indicated by the strong, sharp, and symmetrical 12.4° 2θ line, but presumably due to its

TABLE 3.—*X-ray chart of a typical phillipsite-containing sample*
Sample no.: 76-7-100

2θ, CuKα (uncorrected)	d, Å	Intensity (arb. scale)	Mineral
6.3	14.0	3	Chlorite? Mixed-layer clay?
8.8	10.0	9	Illite
10.8	8.19	8	Amphibole
12.4	7.14	55	Phillipsite
13.9	6.37	5	Feldspar
16.5	5.37	15	Phillipsite
17.9	4.96	22	Illite and phillipsite
20.8	4.27	7	Quartz
21.7	4.10	20	Phillipsite
21.9	4.06	32	Plagioclase
26.6	3.35	20	Quartz and illite
27.5	3.24	30	Potassic feldspar?
28.0	3.19	>100	Plagioclase and phillipsite
30.3	2.95	15	Plagioclase?
31.7	2.82	25	Halite
32.7	2.74	17	Phillipsite
33.4	2.68	20	Phillipsite

small amount and tiny grain size cannot be verified by optical means.

Phillipsite has been found with rather high frequency with potassic feldspar. Thus of the five samples definitely containing phillipsite, three also definitely have potassic feldspar, and one a questionable potassic feldspar. Of the three remaining questionable phillipsite samples, one contains potassic feldspar. Many phillipsite samples also contain calcite. As phillipsite is a hydrous calcium-potassium-aluminum silicate, the mutual relationships of these phases, plus illite and kaolinite, and possibly also the mixed-layer clays, constitute an interesting and relatively simple chemical system for study. This will be undertaken in a separate contribution.

The Phyllosilicates

The phyllosilicates that have been found in the Peru-Chile Trench cores include illite, chlorite, kaolinite, mixed-layer clays, glauconite, and biotite.

Illite, biotite, and glauconite.—Illite is used in the sense of Grim (1953, p. 35), and applies to all platy minerals which give a strong X-ray reflection at about 10 Å. It thus includes possible glauconite in the sample. Nagelschmidt (1937, p. 519) suggests the use of the (060) line to distinguish the dioctahedral from the trioctahedral micas, a criterion which Brown (*in* Brindley, 1951, p. 159) points out does not apply to glauconite. Moreover, the criterion is unsuitable for samples with minerals such as kaolinite and quartz with interfering diffraction lines (see, for example, Brindley and MacEwan, *in* Brindley, 1951, table XIV, 1, II). Nagelschmidt also suggests (1937, p. 519) that the relative weakness or absence of the 5 Å basal reflection is suggestive of trioctahedral micas. Most of the 10 Å micas from the cores show this relationship. However, this does not seem to be a reliable criterion, as prolonged grinding of natural, coarsely crystalline muscovite by the writer has resulted in the complete obliteration of the 5 Å line while the 10 Å line remains strong.

On the bulk and also the untreated $-1.3\ \mu$ samples, the 10 Å reflection of illite is commonly interfered with by lines from the mixed-layer clays. This interference shows up in the asymmetry of the line, with more abrupt high-angle dropoff. Fortunately, the relative amounts of these clays in the samples studied are such that the peak position of the illite lines can generally be determined without difficulty. This position can then be compared with that after glycol treatment; a lack of shift in the line position is used to ascertain the presence of illite.

As is discussed, the exact nature of the illite is difficult to establish although such information is crucial in any consideration on the origin of the minerals. Microscopically, identifiable micas, all or part of which may give an "illite" pattern by X-ray, belong to four descriptive categories.

1. Large laths of colorless mica which are optically identical with muscovite.

2. Large laths of mica which are pleochroic from yellow to brown. These are biotite grains, and are relatively rare. The occurrences have been noted in table 2. Most likely these laths represent detrital grains.

3. Tiny (about $5\ \mu$ or less), colorless, loose shreds, lath-shaped and invariably length-slow. Birefringence is moderate.

4. A phase that is optically much like the above, but is embedded within grains of volcanic glass in various stages of devitrification. Most of these grains are colorless, but

TABLE 4.—*Comparison of the (010) spacings of muscovite and glauconite*

Sample	(060), Å	(010), Å
Muscovite, source unknown (pegmatite material)	1.50(5)	9.03
Muscovite from slate, Castleton, Vt.	1.50(7)	9.04
Muscovite from slate, Castleton, Vt.	1.50(9)	9.05
Muscovite from slate, Castleton, Vt.	1.50(7)	9.04
Muscovite from Renssalaer, N. Y.	1.50(7)	9.04
Muscovite from slate, Hampton, N. Y.	1.50(8)	9.04
Glauconite, Hazel, N. J.	1.51(6)	9.10
Glauconite, Kent, England	1.51(3)	9.08
Glauconite, Birmingham, N. J.	1.51(4)	9.08
"Glauconite", core 61-5	1.51(2)	9.07

owing to the color of the glass the color of the grains may remain in doubt. The textural relations of the micaceous grains to the glass matrix is variable. For some relatively fresh grains, mica occurs near the grain-boundary of the glass which is otherwise quite fresh; with more advanced devitrification, however, mica may pervade the grains. In many samples, in fact, the only indications of the original glassy nature of the matrix are the enclosed phenocrysts of euhedral feldspar and/or amphibole.

Certainly both the first two types, and probably both the latter types as well, contribute to the 10 Å X-ray reflection. From the appearance of the material under the microscope, much of it may be dioctahedral mica closely akin to muscovite; however this is not a proven point. The existence of a colorless phlogopite, for instance, cannot be excluded.

As table 2 shows, only an extremely limited number of samples does not contain illite. It is found associated with every other mineral except possibly glauconite; the two minerals, however, cannot be easily differentiated by routine X-ray examination even if they do coexist.

Although many of the samples show, under the microscope, an olive-green, fine paste, the mineral glauconite has been definitely identified only in one sample. This is from core 61-5, at depth levels between 102 and 106 cms. The bulk of the core here is a brownish-gray, fine, homogeneous silt, with moderate HCl reactions; scattered through this material are a number of deep green, shapeless, very fine-grained patches, each 1–3 mm across. The boundaries with the matrix are sharp. X-ray examination shows that these green spots have, aside from small amounts of quartz and plagioclase which are also abundant in the matrix material, a very broad reflection centered at about 10 Å. This peak is little affected by heating to 440° C for ½ hour; glycol saturation, however, shifts part of it to nearly 18 Å (4.9° 2θ), but peaks also exist at 14.3 Å, 12.6 Å, and 10.0 Å (6.2°, 7.0°, and 8.8° 2θ, respectively). The (060) line is broad and poorly resolved; its peak, however, is at 61.3° and corresponds to a (010) spacing of 9.1 Å. This mineral, or group of minerals, is identified as glauconite, as well as mixed-layer clays with important glauconite components. Finally, the "glauconite" sample also gives, on the X-ray fluorescence analyzer, an $Fe_{k\alpha_1}$ line with its intensity 2.6 times[3] as strong as the matrix from an adjacent level has yielded.

The value of the (010) spacing of the glauconite, 9.1 Å, is intermediate between the trioctahedral micas like biotite and the dioctahedral aluminum micas like muscovite, but agrees with the (010) of undoubted glauconite. Table 4 gives the X-ray data on a number of muscovite and glauconite samples; for reference, the (010) of muscovite and phlogopite are given as 9.04 Å (Winchell and Winchell, 1951, p. 367) and 9.23 Å (Bragg, 1937, p. 213), respectively.

The enlargement of the (010) dimension of glauconite, as compared to muscovite, is

[3] This ratio has not been corrected for the non-linearity of the Geiger counter in the particular intensity range encountered. The more intense reflection should give a reading relatively too low and so the ratio is a minimum value.

TABLE 5.—*Procedure for the identification of chlorite*

Untreated sample	Code Ethylene glycol saturated	Heated to 350°C
7 Å (A)	Not affected (1)	Not affected (a)
	Shifted (2)	Disappeared (b)
		Diminished (c)
14 Å (B)	Not shifted (3)	Not affected (d)
	Shifted (4)	Disappeared (e)
		Shifted to 10 Å (f)

Scheme for Identification

A-no B-1-a:	Kaolinite
-b:	Chlorite ("Bradley")
-c:	Kaolinite+chlorite ("Bradley")
B-no A-4-f:	Mixed-layer clay
A-B-1-a-3-d:	Chlorite ("Brindley"). Kaolinite?
-e:	Kaolinite+chlorite ("Bradley")
-4-f:	Kaolinite+mixed-layer clay
-b-3-e:	Chlorite ("Bradley")
-4-e:	Mixed-layer clay+chlorite?
-f:	Mixed-layer clay+chlorite?
-c-3-e:	Kaolinite+chlorite ("Bradley")
-4-f:	Mixed-layer clay+chlorite?

None of the other combinations of the code, of which there are 36, have been observed.

presumably due to the substitution of Fe‴ for Al in the dioctahedral positions. A similar relation in the (010) dimensions of beidellite and its ferric analog, nontronite, is reported by MacEwan (*in* Brindley, 1951, p. 106); the (010) increases in this instance from 8.95 Å for beidellite to 9.15 Å for nontronite.

Kaolinite.—The term kaolinite as used here is based virtually exclusively on X-ray records, and has been defined in an earlier paper (Zen, 1959, p. 31). As such, the name applies to any *ca.* 7 Å platy mineral whose basal reflection is not destroyed by heating to about 450° C. In some instances, the $-1.3\ \mu$ fractions show the (002) reflection at 24.9° 2θ which distinguishes it from chlorite, with its (004) reflection at 25.2°; however, this distinction is not always possible as the peaks may not be resolved. The term "kaolinite," as used here, not only fails to differentiate the stacking polymorphs of the various phases in the kaolinite group, but also fails to distinguish such minerals as antigorite, amesite, or the "septechlorites" (Nelson and Roy, 1958, p. 708).

Kaolinite has been found with all the other minerals, including phillipsite and calcite. The only exception is a lack of association with glauconite; this may well be a sampling problem since glauconite was found but once. The phase-equilibrium relation of kaolinite and calcite has been considered elsewhere (Zen, 1959); relation between kaolinite and phillipsite, as well as other essential potassic phases, will be considered in a separate paper.

Chlorite.—The operational definition of chlorite, based on X-ray diffraction, has been set out before (Zen, 1959, p. 31). One practical difficulty in the identification of chlorite is the fact that there are two sets of criteria available (Brindley and Robinson, *in* Brindley, 1951; Bradley, 1954) which are not always mutually compatible. Brindley and Robinson based their criteria on relatively coarse, well-crystallized chlorite (Brindley, 1957, personal communication), whereas Bradley's criteria, based on the presumption of lower thermal stability of chlorite when heated in the open air, are more useful for fine-grained, poorly crystalline chlorite (Bradley, 1957, personal communication). Thus to establish the *existence* of the chlorite phase in a sample, one would have to assume first the nature of the chlorite one is dealing with. Fortunately, in practice the two sets of criteria can be combined to a large extent, and the adapted procedures are outlined by the scheme shown in table 5.

The origin of the two different types of

chlorite is a matter for speculation. The "Brindley" chlorite always gives sharp and symmetrical basal reflections, in contrast to the "Bradley" chlorite which tends to give diffuse and broad basal peaks. These facts are consistent with their presumed state of crystallinity. One is tempted to correlate the "Brindley" chlorite with coarse, detrital flakes and the "Bradley" chlorite with authigenic material, although this point is not established. "Brindley" chlorite is much less common than the "Bradley" chlorite in the samples from the Peru-Chile Trench area. Chlorite as a group, but in particular the "Bradley" type, has been found with all other mineral phases identified in the core samples. It is unfortunate that nothing can be said of the detailed compositions of the chlorite samples from different mineral associations.

Mixed-layer clays and montmorillonite.— In the preliminary report (Zen, 1957), it was stated that montmorillonite is rare and mixed-layer clays not found in the Peru-Chile cores. Since the writing of that report, more detailed work on the $-1.3\ \mu$ fractions has shown this to be incorrect. Instead, mixed-layer clays turn out to be among the most common minerals in the core samples.

In an air-dried sample, most of the material shows a broad reflection between 6.0° and 7.5° 2θ (14.7 Å to 11.8 Å) but commonly centered about 6.5° (13.6 Å). Glycolation shifts this spectrum of reflections to a broad peak centered commonly around 5.3° (16.7 Å). The diffraction lines are unaffected by heating to around 200°C in open air for one hour, but collapse to about 10 Å upon heating to around 450°C for one-half hour in the open air.

The results of heat treatment indicate that the non-expanding layers are 10 Å material, perhaps muscovite-type layers. The results of glycolation show that, for much of the material, about 80 percent of the layers are expandable (Weaver, 1956, p. 206). Using this information, it is then possible to say that the untreated expandable layers have basal spacing of about 14 Å. The broadness of the lines, both in untreated and glycolated material, may indicate that a collection of mixed-layer material, with the 10 Å and 14 Å layers in variable proportions, exists in many of the samples. This accords with the observation of Weaver (1956, p. 210) on the clay mineralogy of some sedimentary rocks.

In many samples, for instance 53-5-120, the untreated $-1.3\ \mu$ fraction gives, in addition to the broad peak between 6.0° and 7.5° 2θ, a rather well-defined peak at 8.2° 2θ, or 10.8 Å. Using the migration chart of Brown and MacEwan (*in* Brindley, 1951), this might be interlayered 10 Å type with (a) 30% 12.4 Å type; (b) 20% 14 Å type; or (c) 15% 15.4 Å type. Glycolated samples yield a line at 13.4 Å; using Weaver's migration chart (1956, p. 206), the first choice is accepted.

As another example, specimen 54-5-114 gives, in addition to a broad peak between 6.0° and 7.0° 2θ, a peak at 7.6°. This peak is associated with a 5.7° peak for the glycolated sample, and is taken to be 55% 12.4 Å layers mixed with 10 Å type. In addition, a 5.7° peak of the untreated sample (15.5 Å) is taken to be nearly pure two-layer montmorillonite.

These are but a few typical examples; many other $-1.3\ \mu$ samples from different cores give similar results. It is clear that mixed-layer clays involving different types of layers occur, as well as those involving different proportions of the same types of layers.

The 12.4 Å layers may be attributed to one-layer hydration (Bradley, Grim, and Clark, 1937, p. 221), or may be due to Na or K adsorption (Weaver, 1956, p. 205). The 14 Å type layers may be due to Ca-adsorbed layers with octahedrally coordinated H_2O (MacEwan, *in* Brindley, 1951, p. 110), but may also be due to vermiculite layers. The 15.5 Å type is probably simple two-layer H_2O type.

Halite

Halite is a very common mineral in the core samples, and is easily identified by the (200) line at 31.8° 2θ on the X-ray chart. When very abundant, its (111) line at 27.5° 2θ interferes with the potassic feldspar line.

Halite is, without much doubt, the result of dehydration of the cores. It is weak to absent in highly permeable, sandy cores, but is

especially important in cores made up largely of tests of microorganisms which offer many traps for water.

Gypsum

Gypsum is found in some cores, presumably as a phase resulting from the drying up of the entrapped sea water. The diagnostic line used on the X-ray chart is at 11.8° 2θ, which is destroyed by heating of the sample to 450°C.

Glass

Volcanic glass is, quantitatively, a very important phase in many of the core samples. Being non-crystalline, it is not recorded by X-ray diffraction; optical examination alone establishes its presence.

Volcanic glass occurs typically as angular to subrounded fragments, commonly mixed with the rest of the material but rarely (as in core 70-7 and 73-6) forming thin but nearly pure layers. The material is devitrified to different extents, as can be seen even in a single oil-immersion mount; it ranges from completely fresh and clean to completely altered material, the latter recognizable as devitrified glass only by the enclosed euhedral phenocrysts. The fresh material ranges in refractive indices from near 1.50 to 1.56 or more. Presumably this range reflects differences in chemical composition, from rhyolitic to basaltic glass (Wahlstrom, 1955, p. 288). The glass with low refractive index tends to be colorless, where even tiny fragments of those with high indices are commonly olive-green to olive-brown.

FOSSILS

No specific study has been made of the fossil records of the Peru-Chile cores. The brief notes below are observations incidental to the mineralogical studies.

The fossil remains can be conveniently divided into two groups: the calcareous forms and those which, under the microscope, are completely isotropic and which on the X-ray chart leave no record. This latter type is presumably composed of amorphous silica.

The calcareous fossils may be composed of aragonite, but much more commonly the carbonate is calcite. In fact, most of the calcite in the samples may be correlated with fossils. Megascopic fossils such as gastropod and pelecypod shells are fairly common, particularly in the coarser-grained, nearshore (landward of the Trench axis) material; more commonly, however, the fossils are microscopic, including abundant foraminifera. These occur in the fine mud as well as in the coarse material. Locally such material makes up nearly the entire core, as for example core 65-6, a substantial part of which is composed of 1 mm size foraminifera; and core 39-3, the lower portion of which is a white chalky deposit of globigerina ooze.

The siliceous fossils are extremely common in all the cores. These are always microscopic in size and commonly fragmentary.

SEDIMENTARY FEATURES

The sedimentary structures to be described in this section are necessarily rather small-scale phenomena, limited by the diameter of a core. It has not been possible to correlate such data as the spacing and nature of bedding from one core to another, partly from lack of information on the time-equivalence among the cores, and partly because of sparsity of cores compared to the size of the area covered.

Size Distribution

Quantitative study of the size distribution in the cores is being reported by P. D. Trask of the University of California and is outside the scope of this report. The following generalizations, based on the megascopic data of table 1, however, may be of interest.

West of the Peru-Chile Trench axis, the cores are uniformly of fine mud, the individual grains too small to be seen with the naked eye. Along the Trench axis, the material is mainly fine mud, but interlayering of seams of silty sand is quite common (cores 20-2, 55-5, 70-6, 77-7). These silty sands tend to be rather thin-bedded, each individual layer no more than a few inches thick, and commonly have sharp boundaries against the muddy matrix. Moreover, the sand is generally well-sorted, and either loosely cemented or uncemented.

Shoreward from the Trench axis, silty to sandy cores become much more prevalent. Although the most shoreward core of each traverse tends to be most sandy, the distri-

bution of sand and silty mud does not seem to correlate simply with distance from shore along any given traverse. Either sand, or silt, or both, may also be interbedded with fine mud in a given core. Finally, between cores of relatively coarse material, fine clayey mud cores may occur. Core no. 59-5, for example, is fine mud throughout, and is located between a silty core no. 60-5 and a sandy-silty core 58-5. Likewise, core no. 67-6, of fine mud, is found between no 68-6, with silty material, and no. 65-6, of silt and sand. On the basis of available information (Zeigler and others, 1957, pp. 243–244), these patterns of distribution do not seem to be attributable to the bottom topography.

It would be interesting to know the mode of transport of the relatively coarse material into the axial portion of the Trench. Much of the coarse material consists of thin, clearly-defined beds of well-sorted material. Furthermore, coarse material is wanting seaward of the Trench axis. These facts indicate that bottom currents, rather than wind or surface currents, may be the dominant agent of transportation for sediments of this size range (see also Schmalz, 1958, p. 107). Unfortunately, data on deep-water currents in this area are lacking.

Bedding

Because the cores are extremely superficial samples of the sediments, large-scale bedding cannot be seen. Bedding, as it is observed, may be gradational or sharp, and individual beds range in thickness from a fraction of a millimeter on up.

Graded bedding has been found in a number of cores. Examples are core nos. 20-2, 31-3, 70-6, 78-7, and 79-7; the gradation is always "normal," the sandy beds possessing sharp bottom contacts but grading upward into fine mud. Perhaps the most striking instance of graded bedding is core no. 31-3, between levels 21 and 23 cms; here graded bedding is the result of size gradation of tests of siliceous microfossils. The graded bedding in this core, and in core no. 79-7, are well-sorted; the other examples show poor sorting, with gradation of the maximum grain sizes.

Cross-bedding has been found in two samples. One is core no. 31-3, depth levels 110–116 cms; the cross-bedding, with laminae about 1 mm thick, spanning the 6 cm interval, is due to interlayering of white siliceous microfossil tests and dark mud. The second, and more questionable, instance is core no. 55-5, depth levels 124–126 cms; "cross-bedding" is due to 1–2 mm layers of medium sand separated by dark, muddy partings. In both examples, the cross-bedding is normal in that the beds are tangent to the bottom and truncated at the top. Unfortunately, the orientation of the features in the horizontal plane is unknown, so that an interpretation cannot be made of the direction of bottom currents.

GEOLOGIC IMPLICATIONS

One of the clearcut results of this study is the variation of grain size with distance from the shore to the Trench axis, already described. It should be emphasized, however, that this seaward decrease in size is not necessarily true in detail, so that a core of fine sediment may in fact be found between two cores of coarser material; landward of the Trench axis local variations of sediment grain size span the entire size-range so far found.

Because of the relative sparsity of cores, as well as lack of three-dimensional control on the bottom topography, it is impossible to say how extensively the lithologic types persist. Although most of the cores are of fine mud, one is not justified in correlating them as one individual unit. The sedimentary types may be quite variable. Thus, upon diagenesis, core no. 31-3 may well become an impure chert bed; 36-3 a shale, and 39-3 in part a chalky limestone. Many of the cores will become fine-grained arkose, feldspathic sandstone, or subgraywacke; whereas at least one core, no. 1-1, which was a dark gray, hydrogen-sulfide smelling fine mud, that oxidized in a few days to a reddish-brown color, might well become a black shale deposit.

The cores tend to show little overall lithologic variation along their length, the common small-scale variations averaging out over the length of the core. Since the longest core is less than 10 feet, however, it is not possible to state what vertical changes there may be in the sediments as a whole. There are no data for estimating the thicknesses

of the sedimentary columns in this area, on the basis of the present study.

The finding of volcanic glass in the sediments is of stratigraphic as well as petrologic interest. Glass fragments are so plentiful in many of the samples that the beds may well be termed ash deposits. Other samples, however, show admixture of quartz, carbonate (at least in part organic remains), and possibly other minerals in variable amounts, so that the resulting rocks might, when indurated and perhaps later metamorphosed, be expected to show mineral assemblages different from either greenstones on one hand and ordinary clastic shales on the other. A proper appreciation of the genesis of these beds is clearly essential to the interpretation of the geologic history from the sedimentary records, for areas of similar tectonic conditions.

The possible correlation of the mineralogy of the cores with the provenance areas has been studied by Schmalz (1958), to whose work the reader is referred.

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REFERENCES

BRADLEY, W. F., 1954, X-ray diffraction criteria for the characterization of chloritic material in sediments. *In* Clays and clay minerals, Publ. no. 327, Nat. Acad. Sci. and Nat. Res. Council. p. 324–334.

———, GRIM, R. E., AND CLARK, G. L., 1937, A study of the behavior of montmorillonite upon wetting: Zeit. Krist. v. 97, p. 216–222.

BRAGG, W. L., 1937, Atomic structure of minerals. Cornell University Press, Ithaca, New York. 292 p.

BRINDLEY, G. W., ed., 1951, X-ray identification and crystal structures of clay minerals: The Mineralogical Society, London. 345 p.

———, ed., 1958, X-ray powder data file. Am. Assoc. Testing Materials Spec. Publ. 48-G.

CLARK, S. P., JR., 1957, A note on calcite-aragonite equilibrium: Am. Mineralogist v. 42, p. 564–566.

EWING, M., HEEZEN, B. C., AND ERICSON, D. B., 1959, Significance of the Worzel deep sea ash: Nat. Acad. Sci. Proc. v. 45, p. 355–361.

GRAF, D. L., AND GOLDSMITH, J. R., 1956, Some hydrothermal syntheses of dolomite and protodolomite: Jour. Geology v. 64, p. 173–186.

GRIM, R. E., 1953, Clay mineralogy. McGraw-Hill Book Company, New York. 384 p.

GUNTHER, E. R., 1936, A report on oceanographical investigations in the Peru coastal current. *Discovery* Repts. v. 13, p. 107–276.

JAMIESON, J. C., 1953, Phase equilibrium in the system calcite-aragonite: Jour. Chem. Phys. v. 21, p. 1385–1390.

JENKS, W. F., 1946, Preliminary note on geologic studies of the Pacific slope in southern Peru: Am. Jour. Sci. v. 244, p. 367–372.

———, ed., 1956, Handbook of South American geology. Geol. Soc. America Mem. 65, New York. 378 p.

MACDONALD, G. J. F., 1956, Experimental determination of calcite-aragonite equilibrium relations at elevated temperatures and pressures: Am. Mineralogist, v. 41, p. 744–756.

NAGELSCHMIDT, G., 1937, X-ray investigation on clays, Pt. III: Zeit. Krist v. 97, p. 514–521.

NELSON, B. W., AND ROY, R., 1958, Synthesis of the chlorites and their structural and chemical constitution: Am. Mineralogist v. 43, p. 707–725.

REVELLE, R. R., 1944, Marine bottom samples collected in the Pacific Ocean by the *Carnegie* on its seventh cruise: Carnegie Inst. Wash. Publ. 556, Pt. 1, p. 1–180.

———, 1958, The *Downwind* expedition to the southeast Pacific (abs.) Am. Geophysical Union Trans. v. 39, p. 528.

RÜEGG, W., 1957, Geologie zwischen Cañete-San Juan 13°00′–15°24′ Südperu. Geologische Rundschau v. 45, p. 775–858.

SCHMALZ, R. F., 1958, A technique for quantitative modal analysis by X-ray diffraction and its application to modern sediments of the Peru-Chile Trench. Harvard University Thesis. 150 p.

———, AND ZEN, E. (in prep.), Quantitative modal analysis of sediments by X-ray diffraction.

SMITH, J. V., 1956, The powder patterns and lattice parameters of plagioclase feldspars. I. The soda-rich plagioclases: Mineralog. Mag. v. 31, p. 47–68.

WAHLSTROM, E. E., 1955, Petrographic mineralogy. John Wiley and Sons. New York. 408 p.

WEAVER, C. E., 1956, The distribution and identification of mixed-layer clays in sedimentary rocks: Am. Mineralogist v. 41, p. 202–221.

WINCHELL, A. N., AND WINCHELL, H., 1951, Elements of optical mineralogy. Part II. John Wiley and Sons. New York. 551 p.

WORZEL, J. L., 1959, Extensive deep sea sub-bottom reflections identified as white ash: Nat. Acad. Sci. Proc. v. 45, p. 349–355.

ZEIGLER, J. M., ATHEARN, W. D., AND SMALL, H., 1957, Profiles across the Peru-Chile Trench: Deep-Sea Research, vol. 4, p. 238–249.

ZEN, E., 1957, Preliminary report on the mineralogy and petrology of some marine bottom samples off the coast of Peru and Chile: Am. Mineralogist v. 42, p. 889–903.

———, 1959, Clay mineral-carbonate relations in sedimentary rocks: Am. Jour. Sci. v. 257, p. 29–43.

———, (in press), Carbonate equilibria in the open ocean and their bearings on the interpretation of ancient carbonate rocks: Geochim. et Cosmochim. Acta.

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FIGS. 1–5, DECEMBER, 1959

PETROGRAPHY OF SOME MINNESOTA TILLS[1]

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ABSTRACT

Wisconsin tills in Minnesota may be assigned to different ice lobes depending primarily upon the color, texture, stone content, and other petrographic characteristics. These petrographic features have their origin chiefly in distinctive types of bedrock in Minnesota and adjacent areas. The Precambrian rocks that underlie the drift over most of the state include red sandstone and slate in a belt extending south-southwest from the head of Lake Superior; basalt, felsite, gabbro, anorthosite, and related rocks in the highland north of Lake Superior; iron formation; and various metamorphic and granitic rocks. Paleozoic carbonate rocks are found principally in southern Manitoba but also in southeastern Minnesota. Cretaceous shale occurs in the area of the Red River Valley and in southwestern Minnesota.

The configuration of the several ice lobes was determined partly by the presence of lowlands in the bedrock, notably one following the Red River-Minnesota River valleys (Des Moines lobe) and one following a lowland extension of the Lake Superior basin (Superior lobe). The central part of the state was occupied by the Wadena lobe and the Rainy lobe, and their directions of movement were probably controlled by mutual interference as well as by pre-existing topography.

The Wisconsin glacial history in Minnesota was marked also by repeated advances of the several ice lobes. In the case of the Superior lobe the tills assigned to the Cary and Valders advances may be identified texturally because the Valders till was formed by the incorporation of lake clays deposited in the Lake Superior basin during the Two Creeks interstadial just preceding, whereas the Cary Superior till is sandy. A Mankato Superior till, identified on morphologic grounds, appears to have an intermediate (silty) texture.

Of the two tills of western source, the Wadena is the more sandy, probably because the Des Moines till passed over Cretaceous shale. The tills of the Rainy lobe and its two sublobes (Pierz and Brainerd) are all sandy and are stonier than the tills of the other lobes.

Stone counts are perhaps the most diagnostic petrographic characteristic of Minnesota tills. They are easily made and generally point to the correct assignment. Difficulties occur where tills contaminate one another in contact zones. Color distinctions, as measured by the Munsell color chart or in the laboratory by the Clark-Maxwell method, are also generally distinct.

Heavy-mineral analyses and clay-mineral analyses are of limited use in differentiating tills. They are time-consuming and not particularly diagnostic.

INTRODUCTION

The glacial deposits of Minnesota were first studied and mapped by Winchell and Upham (1888), who differentiated two principal types of till, a red to brown till with source in the Precambrian rocks to the northeast and a yellow to gray calcareous till with source in the Paleozoic and Cretaceous rocks to the northwest. Leverett (1932) prepared a more detailed map showing the distribution of these two principal types of till and referred the tills to three presumed centers of ice flow in Canada, namely the Keewatin, Patrician, and Labradorean. He worked out the age relations largely on the basis of morphologic features. More recent work by the Minnesota Geological Survey (Wright, 1956; Schneider, 1956, in press), which has been concerned with the lithologic and stratigraphic relations of the drifts as well as the morphologic, has led to the recognition of at least six major lithologic till types instead of the two distinguished by Leverett. Three sub-ages of ice advance during the Wisconsin glacial age have been identified instead of the two described by Leverett.

The lithology of Minnesota tills must be interpreted in relation to the bedrock map of Minnesota and adjacent regions (fig. 1) and in relation to the pre-glacial topography. The character of the source rocks is generally the main factor in controlling the texture, stone content, mineralogy, and chemical composition of the tills, and the location of bedrock lowlands determined the paths of movement of ice lobes protruding

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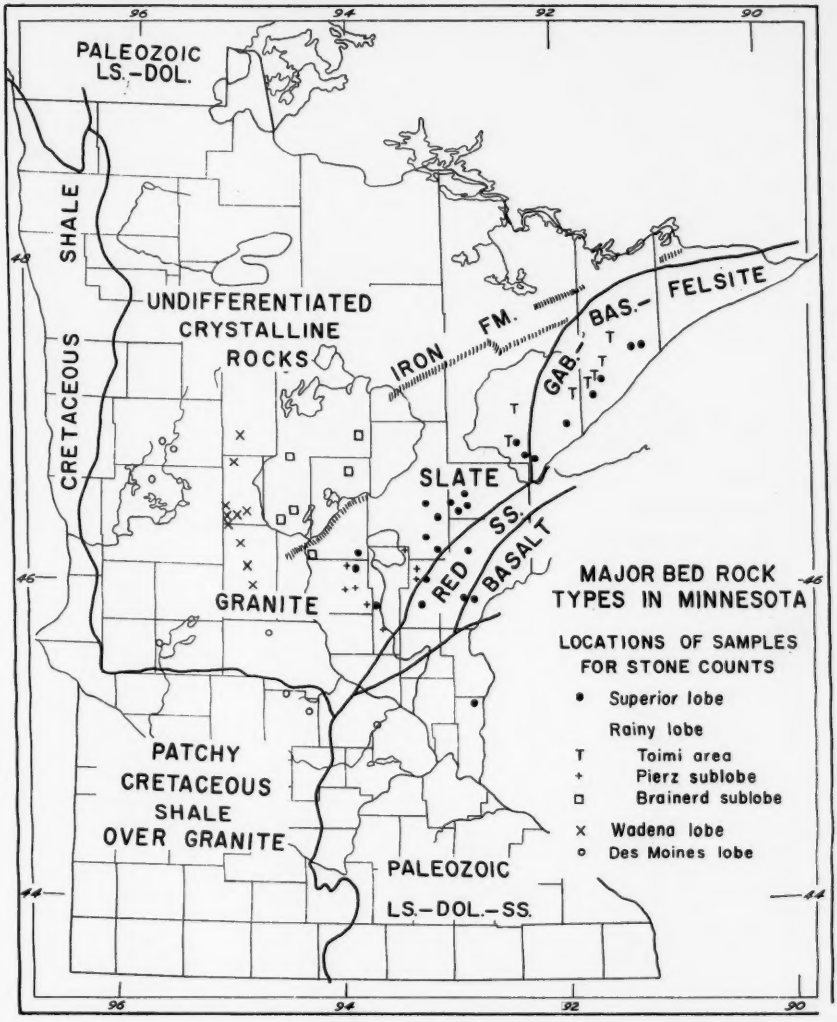

FIG. 1.—Bedrock map of Minnesota, showing locations of samples for stone counts.

from the main ice sheet. The region includes three contrasting rock provinces, so that ice lobes entering the state from different directions brought till of contrasting lithology. The largest province is that of the Precambrian rocks. Distinctive among these are (1) the red sandstone and slate southwest of the Lake Superior basin, (2) the gabbro, red granophyre, felsite, and basalt of the Lake Superior highland, and (3) the iron formations of the Mesabi, Cuyuna, and Vermillion iron ranges. Other Precambrian

TABLE 1.—*Terminology of Wisconsin drifts in Minnesota*

Substage	Lobe	Usual color & texture of till	Immediate source	Leverett's correlation
Valders	St. Louis sublobe of Des Moines lobe	Buff silty	Red River Valley	Late Wisconsin Keewatin drift
	Superior	Red clayey	Superior basin	Late Wisconsin Labradorean drift
Two Creeks Interstadial				
Mankato	Des Moines lobe, Grantsburg sublobe	Buff silty	Red River Valley	Late Wisconsin Keewatin drift
	Superior	Red silty?	Superior basin	Middle and Late Wisconsin Patrician and Labradorean drift
Cary	Rainy	Gray sandy	NE Minn.	Mid-Wisconsin Patrician drift
	Brainerd sublobe	Brown sandy	NE Minn.	Mid-Wisconsin Patrician drift
	Pierz sublobe	Brown sandy	NE Minn.	Mid-Wisconsin Patrician drift
	Superior	Red sandy	Superior basin	Mid-Wisconsin Patrician drift
	Des Moines	Buff silty	Red River Valley	Late Wisconsin Keewatin drift
	Wadena	Buff sandy	Winnipeg lowland	Iowan (?) Keewatin drift

rock types of importance are the granites of central and northern Minnesota and the slate, graywacke, and other metamorphic rocks of the northeast and north. Because of the wide distribution of granite and metamorphic rocks in northern Minnesota and adjacent Canada, these rocks are not so significant as drift indicators.

The second major rock province in the region is that of the Paleozoic limestone and dolomite of the Winnipeg lowland. Paleozoic sedimentary rocks occur also in southeastern Minnesota, but this area is too far south to have had effect on the lithology of most of the deposits under consideration.

The third province is that of the Cretaceous shale, found in the Red River Valley of western Minnesota and adjacent Manitoba and the Dakotas, as well as in southwestern Minnesota.

Two major bedrock lowlands controlled movement of ice lobes in the state: (1) the Red River Valley and its continuation, the Minnesota River Valley, and (2) the Lake Superior basin and its southwestward extension to the Minneapolis area and beyond to the Minnesota River Valley. Prominent upland areas include the Lake Superior highland north of the lake, and a high area in west-central Minnesota.

The ice lobes and corresponding tills now recognized in Minnesota are summarized in table 1 in chronological arrangement, and a simplified version of the sequence is presented in figure 2. All four major ice lobes were active during the Cary sub-age. During the Mankato and Valders sub-ages the movements were more restricted, or at least have not been fully identified. The tills may be grouped as the gray or buff calcareous tills of western source (Keewatin of Leverett) and the red to brown generally noncalcareous tills of eastern source (Patrician and Labradorean of Leverett). The major western ice lobe was the Des Moines lobe, which occupied the Red River-Minnesota River Valleys and sent sub-lobes northeastward past Minneapolis (Grantsburg sublobe) and eastward toward Lake Superior (St. Louis sublobe). It carried a gray (buff where oxidized) generally silty till with Paleozoic carbonates from the Winnipeg lowland and Cretaceous shale from the Red River and Minnesota River Valleys. A second western ice lobe was the Wadena lobe, which is believed to have moved southeastward from the Winnipeg lowland into north-central Minnesota and thence

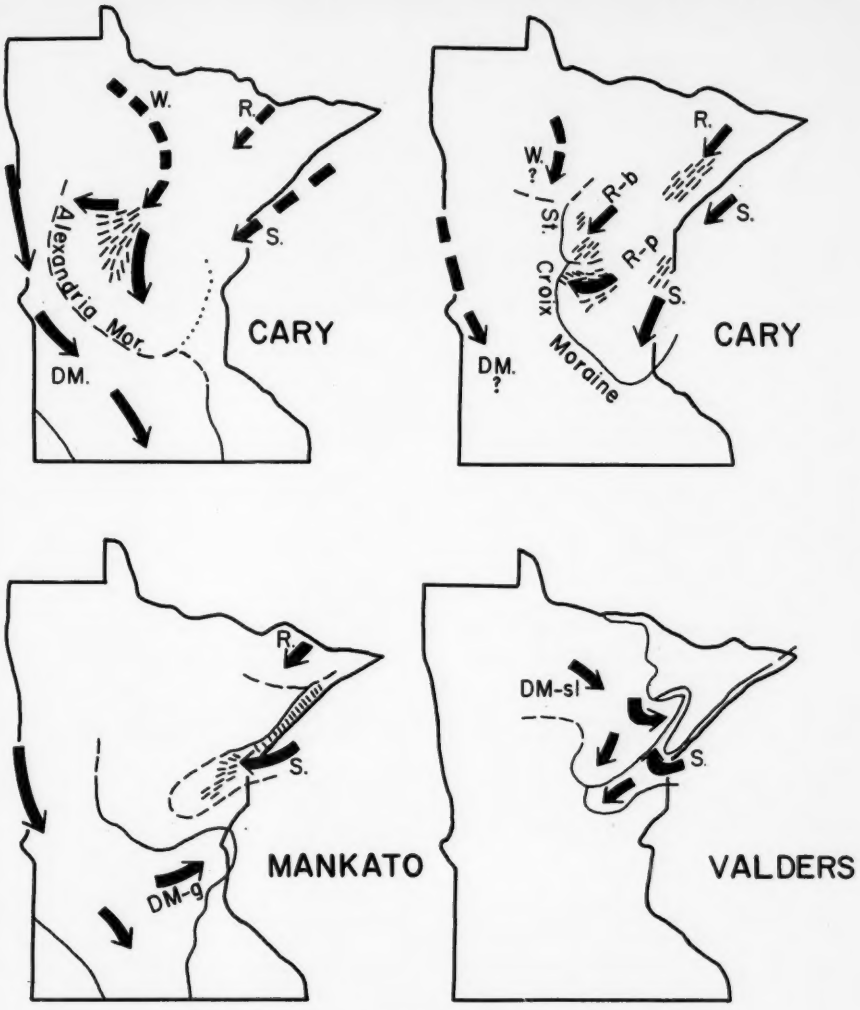

FIG. 2.—Sequence of Wisconsin glaciation in Minnesota.

southwestward to west-central Minnesota. It brought a gray to buff calcareous sandy till with Paleozoic carbonates but no Cretaceous shale.

Eastern ice lobes include the Superior lobe and the Rainy lobe. The Superior lobe extended southeast from Lake Superior and deposited red sandy till derived largely from the Precambrian red clastic rocks of this region. The Rainy lobe moved southwestward over the area of gabbro and volcanic rocks north of Lake Superior and pro-

duced a gray sandy till in this region, well expressed in the Toimi drumlin field. It is believed to have extended southwestward in two tongues which approached central Minnesota from different directions; these have been called the Pierz and Brainerd lobes (or sublobes), both characterized by brown sandy till.

The post-Cary ice movements in Minnesota were more closely confined to the principal bedrock lowlands. The tills resemble the Cary tills of the same lobes except that the Valders Superior till is highly clayey, presumably because of incorporation of red lake clays deposited in the Superior basin during the Two Creeks Interstadial just preceding.

Till forms the parent material of a great many Minnesota soils, and the characteristics of these soils depend to a large extent on the lithology and texture of the parent materials. In fact, the identification of soil series in this region depends on the proper recognition of the parent material. The new till identifications have already led to refinements in soil mapping and will necessitate further revisions. The several tills may generally be identified in the field by texture, color, and stone content. The present paper describes laboratory analyses of these and other lithologic features to show quantitatively the extent of the variations.

The work was started independently by the authors in connection with research respectively on soils genesis and Pleistocene history. Although the methods of sampling and analysis differed slightly, the results are generally complementary and are therefore presented jointly.

Assistance in the laboratory analysis was made possible by research grants afforded separately to the two authors by the Graduate School of the University of Minnesota, and the work was carried out in the laboratories of the Department of Soils and Geology. X-ray analyses were kindly read by Professor J. W. Gruner of the Geology Department.

SAMPLING AND METHODS OF ANALYSIS

Samples of till were collected from road cuts at depths well below the solum, that is, usually 6–10 ft below the surface. These samples were used in the laboratory for particle-size analysis and mineralogical and color determinations. In addition, in the case of samples A-1 to A-14 collected by Arneman, large bulk samples of till were washed to allow the separation of pebbles (4–64 mm) and granules (2–4 mm) for stone counts. The other counts were made from approximately 100 stones collected directly in the field from cleaned exposures.

Stone counts were made with the aid of hand lens, binocular microscope, and standard tools for rock identification.

Particle-size analysis of the sand size grades were made with the use of sieves. The sieves used by Wright were calibrated according to the Wentworth system, so the results were recomputed from the cumulative curves to conform with the U. S. Department of Agriculture separations employed by Arneman for samples A-1 to A-14.

Particle size analysis of the silt and clay fractions were made by the pipette method of Kilmer and Alexander (1949) with minor variations. Sodium hexametaphosphate-sodium carbonate was used to aid dispersion (Tyner, 1940). Again the size limits for the Wright analyses were adjusted from the Wentworth system to the U.S.D.A. system to allow comparisons.

Heavy minerals in the fine and very fine sand fractions were separated with the use of bromoform (sp. gr. 2.85), in the manner described by Arneman, Khan and McMiller (1958) and were mounted in Canada balsam and counted with a petrographic microscope.

X-ray analyses of coarse and fine clays were made with the use of standard X-ray diffraction equipment having unfiltered iron radiation and a camera radius of 57.3 cm. The samples were prepared by centrifuging as described by Arneman, Khan, and McMiller (1958, p. 12).

Chemical analyses of samples A-1 to A-14 involved determination of total potassium and total exchange capacity on coarse and fine clays. The potassium content was determined in the flame photometer by the direct intensity method. The total exchange capacity was determined by standard methods of base exchange.

Color analyses were made on samples A-1 to A-14 by the Clark-Maxwell method (Munsell, 1936), which shows the relative amounts of white, black, red, and yellow.

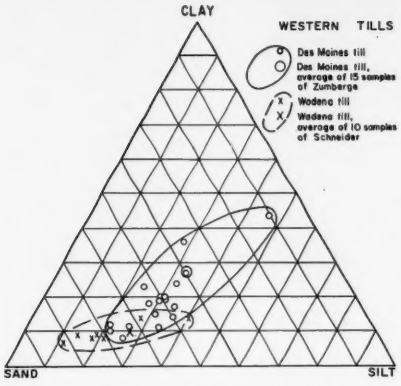

FIG. 3.—Particle-size analyses of Des Moines and Wadena tills.

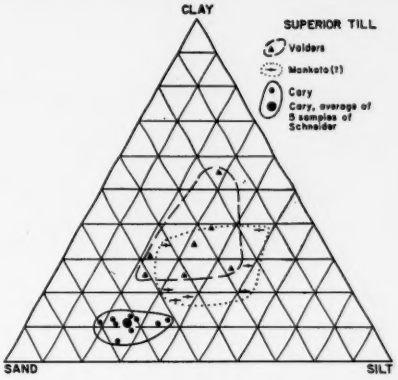

FIG. 4.—Particle-size analyses of Superior tills.

RESULTS AND DISCUSSION

Size Analyses

The results of the particle-size analyses are plotted on triangular diagrams to show the sand-silt-clay ratios. Figure 3 compares the Des Moines and Wadena tills. Field descriptions usually characterize the former as silty till and the latter as sandy till, and this distinction is confirmed in general by the size analyses. Samples represent widely separated localities, and such overlap as exists in the size ranges may probably be attributed to local variability of source materials. The higher content of clay in the Des Moines till is tentatively ascribed to the comminution of fragments of Cretaceous shale. The higher content of sand in the Wadena till probably reflects disintegrated granitic rocks.

Figure 4 compares the Superior tills. The Valders Superior till is recognized in the field by its high clay content and by its patchy distribution near the head of Lake Superior. The high clay content is interpreted as a result of reworking of lake deposits that had been formed in the Superior basin during the Two Creeks Interstadial (Wright, 1955; Murray, 1953). At the other textural extreme is the red sandy Superior till in the east-central part of the state, deposited during the Cary advance. Intermediate between these two textural types is a till labeled in the field as "silty." It is found southwest of the head of Lake Superior in the drumlins and related features tentatively assigned to a post-Cary pre-Valders readvance of the Superior lobe (Mankato; see Wright, 1956, 1957). At the few places where it has been found overlain by the stone-poor clayey Valders till (Finlayson, Paupores), the two tills have distinctly different texture. Elsewhere in this area the assignment of this till to the clayey, silty, or sandy varieties is often difficult, and the legitimacy of a separate silty till is not yet established.

Figure 5 compares the till of the Rainy lobe of the Toimi area north of Lake Superior with the till of its sublobes Pierz and Brainerd. All of these materials are characterized in the field as sandy and stony. The source materials are largely igneous and metamorphic rocks.

Stoniness of the tills was determined by measurement of the percentage of granules and pebbles in bulk samples A-1 to A-14. The results (table 2) show that the content of granules (2–4 mm) in all tills has the narrow range of 2–5 percent, but that the content of pebbles (4–64 mm) shows a greater variability. The total content of granules and pebbles in the Des Moines, Wadena, and Superior tills ranges from 7 to 14 percent, whereas the Brainerd and Pierz

FIG. 5.—Particle-size analyses of Rainy tills.

tills are much stonier, with 17–30 percent pebbles and granules.

Stone Counts

Rock types were grouped into the seven major categories described below, set up according to the main areas of bedrock distribution in Minnesota and areas adjacent to the north (tables 3 and 4). Averages are computed and compared with averages from other studies recently made in the State.

TABLE 2.—*Stoniness of tills*

Sample and location	Pebbles %	Granules %	Total %
Des Moines till			
A-1 Vergas	7.0	4.2	11.2
A-2 Detroit	10.9	3.1	14.0
A-3 Detroit	7.4	4.8	12.2
Average	8.4	4.0	12.4
Wadena till			
A-4 Park Rapids	7.6	3.6	11.2
A-5 Sebeka	6.0	3.5	9.5
A-6 Blue Grass	8.0	4.7	12.7
A-7 Verndale	10.0	4.0	14.0
Average	7.9	3.9	11.8
Brainerd till			
A-8 Emily	12.4	4.1	16.5
A-9 Ft. Ripley	14.6	5.2	19.8
Average	13.5	4.6	18.1
Pierz till			
A-10 Hillman	13.7	4.9	18.6
A-11 Hillman	15.0	4.0	19.0
A-12 Bock	25.9	3.6	29.5
Average	18.2	4.2	22.4
Superior till			
A-13 Quamba	10.9	2.9	13.8
A-14 Scandia	4.9	2.2	7.1
Average	7.9	2.5	10.4

(A) North Shore type. The north shore of Lake Superior and the highland immediately to the northwest are underlain by Keweenawan flows of basalt and felsite and by the Duluth Gabbro with its special rock types diabase, anorthosite, and red granophyre. It is likely that basalt, gabbro, and diabase also occur locally in the bedrock of poorly known areas of north-central Minnesota, and in fact they have been reported from wells in this region. Consequently even the drifts of western source have an appreciable "background" percentage of these rock types. Distinctive types that are probably diagnostic of the North Shore region itself include amygdaloidal basalt, agate, red and purple felsite, and red granophyre ("redrock"). The felsite and "redrock" are listed separately under this grouping because of their general ease in recognition and their probable restricted distribution.

(B) Sandstone. Red to yellow sandstone and red slate occur as a single belt extending south-southwest from the head of Lake Superior toward Minneapolis. It is not known whether these rocks underlie Lake Superior itself.

(C) Granitic rocks. These include granite, diorite and intermediate types, and also granite gneiss and vein quartz. Bedrock of these types is widely distributed in central and northern Minnesota and adjacent Ontario.

(D) Metamorphic rocks include slate, phyllite, schist, quartzite, graywacke, and greenstone. These types are also found in bedrock broadly over northern Minnesota, and their percentage in a drift is therefore usually not diagnostic.

(E) The iron-formation category includes taconite, jaspilite, black chert, and limonite rock and is separated as a group because of the limited outcrop area of these distinctive rock types in northern Minnesota—the Vermillion, Mesabi, and Cuyuna iron ranges and their extensions. Some iron-formation pebbles (and also erratics of native copper) may come from the ranges of northern Wisconsin and Michigan. Most of the stones are extremely durable so that they may have

TABLE 3.—*Stone counts of tills in percent*

Sample number and locality	A. North Shore 1. Felsite	2. Redrock	3. Bas-gab-diabase	B. Sandstone	C. Granitic	D. Metamorphic	E. Iron formation	F. Cret. shale	G-1. Ls-dol	G-2. Light chert	Total stones
SUPERIOR TILL											
Red Till											
Sandstone bedrock											
50-129 Beroun	11	7	15	38	13	11	4			1	111
50-135B Finlayson	8	5	27	42	6	8	4				164
55-129 Warman	15	2	60	2	6	11	4				102
A-13 Quamba	20		41	16	16	4	3				123
Slate bedrock											
50-142 Kettle R.	15	4	17	56	4	3	1				107
50-156 Automba	7	11	27	7	17	23	7			1	121
50-157 Salo	7	16	19	6	13	35	4				169
51-164 Split Rock	14	10	27	25	13	6	3			2	131
55-140 Lawler	11		33	13	10	31	2				91
55-141 Ronald	10	1	44		10	29	6				98
55-177B Pine Center	13	7	43		17	12	8				101
55-179 Sullivan L.	10		35	3	30	16	3			3	104
Granitic bedrock											
50-141 Pliny	9	9	30	10	14	24	4				199
55-143 Geise	15	1	32	9	13	17	13				102
55-172 Page	10	6	47	1	8	21	3			4	100
Other bedrock											
50-131B Beroun	18	4	24	12	22	18	2				91
A-14 Scandia	19		41	9	26	4				1	108
Average	12	4	34	15	14	16	4			1	
Schneider ave. of 3[1]	12		34	23	12	16	1		2		
Gelineau ave. of 10 till[2]	9		32	6	18	15	2		16		
Gelineau ave. of 62 gravel[2]	11		27	8	21	16	3		13	1	
North Shore Area											
55-136B Arnold	19	14	57	2	1	5	2				107
55-152 Munger	21	17	47	1	2	9	3				113
55-153B Saginaw	13	9	56	2	4	15				1	102
56-157B Murphy City	25	11	45		6	10	2			1	103
56-158B Spruce Lake	23	14	37	1	6	15	4				104
56-162B McNair	19	7	50	4	7	13					104
56-165B Highland	8	7	50	10	12	10	2			1	99
56-166B Barrs Lake	7	3	74	1	3	12					102
Average	17	10	52	3	5	11	2				
RAINY TILL											
Toimi area											
55- 29B Shaw	16	6	51	1	9	14	3				91
55-153A Saginaw	22	8	55	2	4	7	1			1	103
56-153B McDougall L.	12	10	47	2	15	13	1				102
56-160B Whyte	17	6	51		8	17	1				93
56-161B Cloquet R.	22	5	54	1	4	13	1				97
56-163B Langley R.	15	16	44		8	17					111
56-164B Rollins	14	5	56		7	14	1			2	100
Average	17	8	51	1	9	13	1				

[1] Schneider (in press); samples from Morrison and Todd counties in central Minnesota.

[2] Gelineau (1959); samples from Dakota County, south of Minneapolis; high content of carbonate rocks reflects local Paleozoic bedrock.

[3] Zumberge and Wright (1956); samples from Nicollet, Blue Earth, Waseca, Steele, and Rice counties southwest of Minnesota River.

TABLE 3.—(*continued*)

Sample number and locality	A. North Shore 1. Felsite	2. Redrock	3. Bas-gab-diabase	B. Sandstone	C. Granitic	D. Metamorphic	E. Iron formation	F. Cret. shale	G-1. Ls-dol	G-2. Light chert	Total stones
Pierz Till											
55-130 Warman W.	15	4	47	4	13	14	3				110
55-139 Opstead	19	4	52	3	13	6	1			2	100
55-144 Woodland	9	7	37	2	12	27	6				103
55-173 Page W.	7	7	49	2	15	11	4			5	105
55-176 Harding	8	2	40	2	23	22	3				107
A-10 Hillman	25		37	3	21	10	3				122
A-11 Hillman	28		32	3	25	8	4			1	109
A-12 Bock	21	3	35	3	27	11	1				106
Average	17	3	41	3	19	13	3			1	
Brainerd till											
53-140B Thunder L.	20		26	4	22	10	10			8	50
53-51B Backus	41		35		14	8				2	49
56-220 Motley	7	2	45	1	25	19	1				100
57-12 Pillager	17		32		27	21	3				100
A-8 Emily	12		24	6	32	21	1			4	134
A-9 Ft. Ripley	14		25	9	33	16	3				100
Average	18		31	4	26	16	3			2	
Schneider ave. of 17 Pierz and Brainerd	12		27	1	27	27	6				
WADENA TILL											
56-191B Long Prairie	2		14		8				76		100
56-193 Clarissa			18		23	23	1		45		100
56-194 Bertha			20		15	6			59		100
56-213 Leaf River			11		28	22	1		37	1	100
56-201B Menahga			27		41	19	1		9	3	100
56-203A Central	3	3	38	2	24	17			13		100
A-4 Park Rapids	2		19	1	44	17	2		13	2	124
A-5 Sebeka			14	2	52	10	2		17	3	121
A-6 Bluegrass	2		22	1	42	10			19	3	125
A-7 Verndale	6		23		36	8			25	2	198
Average	1		21	1	31	13	1		31	1	
Schneider ave. of 10[1]	5		21		22	12	1		38	1	
DES MOINES TILL											
51-189D St. Rosa			33		10			4	53		79
51-367 Dassell	1		6		24	6	3	6	54		87
52-72B Rockford	7		4	2	9	2		21	54	2	49
52-76B Cyrus	6		6		2	2		18	65		57
A-1 Vergas			13	1	29	8		5	43	1	135
A-2 Detroit	2		18		19	13		1	46	1	123
A-3 Detroit	2		17		21	6	1	1	50	2	132
Average	4		12	1	17	5	1	7	42	1	
Zumberge average of 19 till[3]				5	16	6		29	34		
Gelineau average of 15 gravel[2]	8		21	5	16	12	2	10	26		

been transported back and forth by different ice lobes during the Pleistocene; to the extent that this has occurred, their utility as indicators is reduced.

(F) Cretaceous shale occurs under the Red River Valley of western Minnesota and adjacent Manitoba and Dakota and also as patches in southwestern Minnesota.

(G) Limestone and dolomite are found in southern Manitoba and in the northwestern

TABLE 4.—*Summary of stone counts of tills in percent*

	A. North Shore	1. Felsite	2. Redrock	3. Bas-gab-diabase	B. Sandstone	C. Granitic	D. Metamorphic	E. Iron fm.	F. Cret. shale	G.1. ls.-dol.	G.2. Light chert
SUPERIOR TILL											
Red (17 samples)		12	4	34	15	14	16	4			1
No. Shore (8)		17	10	52	3	5	11	2			
RAINY TILL											
Toimi area (7)		17	8	51	1	9	13	1			
Pierz (8)		17	3	41	3	19	13	3			1
Brainerd (6)		18		31	4	26	16	3			2
WADENA TILL (10)		1		21	1	31	13	1		31	1
DES MOINES TILL (8)		4		12	1	17	5	1	7	42	1

corner of Minnesota. They are also found in southeastern Minnesota and here have an important local effect on the drift composition.

The stone counts (table 3) show wide ranges in percentages of individual rock types or groups of rock types among samples of the same drift. Inasmuch as the samples were collected from widely separated localities, consideration must be made for the effects of local bedrock, especially where such bedrock occurs at shallow depth and thus was accessible to the Wisconsin ice. Some of the variations and, in fact, the unexpected occurrences may be a result of contamination by stones from an underlying drift of different source, as was shown by Schneider (in press) for the analyses of Superior and Wadena drifts in their area of overlap.

Most of the stone counts were made from a collection of about 100 stones, but tests with a larger number of stones by the writer and by Horberg (Anderson, 1955) have shown that the accuracy is not increased beyond a few percent and that the apparent variation in stone content from place to place is real and cannot be erased. Larger counts might be more accurate with respect to important minor indicators, but in many cases the most critical indicators would not appear in a count of 1000 because they must be searched for with diligence on the washed exposure. This situation applies particularly to Cretaceous shale, which is not durable and readily breaks down to fragments too small to be retrieved in a collection of stones of pebble size.

The following distinctions in stone content among drifts are apparent from the compilations:

(1) Eastern (Superior and Rainy) tills may be distinguished from western (Des Moines and Wadena) tills by absence of limestone and by higher percentages of iron formation and of North Shore types (especially the distinctive indicators red felsite and "redrock").

(2) Des Moines till differs from Wadena till primarily in the presence of Cretaceous shale. Differences in other rock types are noticeable but they are variable and are not as yet readily explainable in terms of source rocks because the bedrock of northwestern Minnesota is not well known.

(3) The Superior till found along the North Shore Highland is rich in the North Shore rock types and deficient in red sandstone—consequently its color is brown rather than red like the Superior till elsewhere which has a high content of sandstone.

TABLE 5.—*Relation between stone counts and stone size. Pebbles 4–64 mm/granules 2–4 mm, in percent*

Sample number and locality	A. North Shore	1. Felsite	2. Redrock	3. Bas-gabbro-diabase	B. Sandstone	C. Granitic	D. Metamorphic	E. Iron Formation	F. Cret. Shale	G-1. Ls-Dol.	G-2. Light Chert	Total Stones
A-1 Vergas		/1		13/6	1/2	29/33	8/4		5/5	43/29	1/	135/190
A-2 Detroit		2/		18/9	/1	19/60	13/6		1/1	46/23	1/	123/265
A-3 Detroit		2/1		17/13	/1	21/55	6/7	1/	1/2	50/21	2/	132/173
A-4 Park Rapids		2/2		19/10	1/	44/64	17/7	2/		13/16	2/1	124/233
A-5 Sebeka		/1		14/13	2/1	52/63	10/5	2/		17/16	3/1	121/157
A-6 Blue Grass		2/1		22/15	1/2	43/63	10/5			19/13	3/1	125/286
A-7 Verndale		6/3		23/8	/4	36/61	8/4	/1	/1	25/16	2/2	198/227
A-8 Emily		12/10		24/14	6/12	32/61	21/2	1/1			4/	134/190
A-9 Ft. Ripley		14/12		25/15	9/4	33/55	16/12	3/2				100/196
A-10 Hillman		25/15		36/25	3/3	21/52	10/1	3/3	1/		1/1	122/184
A-11 Hillman		27/16		31/26	2/9	26/41	10/6	4/2				109/149
A-12 Bock		21/12	3/	31/33	3/6	27/39	11/5	1/5				106/145
A-13 Quamba		20/19		41/39	16/5	16/29	4/5	3/3				123/144
A-14 Scandia		19/19		41/32	9/8	26/36	4/2	/3		1/		108/167

(4) The Rainy till of the Toimi drumlin field between the Mesabi range and the North Shore Highland shows a higher content of rocks of the North Shore type than do the tills of the Pierz and Brainerd sublobes of the Rainy lobe, which have been diluted by granitic rocks of central Minnesota.

(5) The Rainy till of the Toimi area closely resembles the Superior till of the North Shore Highland in stone count, yet the colors of the two drifts are different. More detailed analyses than those summarized here suggest that the steel-gray color of the till of the Toimi area reflects a relatively high content of gabbro and anorthosite compared to the Superior till of the North Shore Highland, which has more basalt and is brown.

The effect of particle size on lithology is seen in a separate compilation (table 5) showing the comparison in samples A-1 to A-14 between the count in the pebble size (4-64 mm) and the count in the granule size (2–4 mm). The most noticeable difference is the much greater proportion of granite fragments, presumably because of the ease of granulation of the rock into constituent crystals or clumps of crystals.

Heavy Minerals

Heavy-mineral analyses were made only on samples A-1 to A-14. The results (table 6) tend to reflect the stone counts. The high content of hornblende in the Wadena and Des Moines tills may be attributed to crushed granite. The Brainerd till is relatively high in ilmenite, perhaps reflecting the high content of metamorphic rocks from central Minnesota. The relatively high content of augite in the Pierz till may be attributed to basic igneous rocks of the North Shore Highland. The red Superior till has intermediate values of ilmenite and augite, perhaps because of sources in both metamorphic and basic igneous rocks.

Heavy-mineral analyses of tills as a means of characterizing and identifying tills is not so productive as stone counts as far as expenditure of time is concerned in the completion of the analyses. Further, the degree of accuracy is removed one step because of difficulties in assigning particular minerals to particular rock types. Where stones are not available, however, as in glaciofluvial sands, heavy-mineral analyses may be useful and do require knowledge of till composition as a basis for comparison.

Clay-Mineral and Chemical Analyses

The dominant constituents of the coarse clay fraction (0.2–2.0 microns), as determined by X-ray analysis, are quartz and feldspar, with calcite present in the calcareous tills. Various clay minerals are present

TABLE 6.—*Selected heavy minerals in fine and very fine sand fraction*

Location	Augite %	Epidote %	Hornblende %	Ilmenite %
Des Moines till				
A-1 Vergas	3.0	8.2	48.0	3.8
A-2 Detroit	1.5	12.4	47.6	2.8
A-3 Detroit	1.2	9.9	44.6	5.7
Average	1.9	10.2	46.7	4.1
Wadena till				
A-4 Park Rapids	7.5	8.8	43.2	5.2
A-5 Sebeka	7.7	5.7	40.9	6.0
A-6 Blue Grass	8.7	6.8	43.4	5.6
A-7 Verndale	9.4	6.1	39.5	8.0
Average	7.8	6.8	41.7	6.2
Brainerd till				
A-8 Emily	14.4	.9	23.2	36.3
A-9 Ft. Ripley	13.6	2.7	16.8	35.7
Average	14.0	1.8	20.2	36.0
Pierz till				
A-10 Hillman	19.0	3.1	21.7	22.9
A-11 Hillman	24.0	1.1	14.8	26.6
A-12 Bock	34.7	1.2	10.8	25.0
Average	25.9	1.9	15.8	24.8
Superior till				
A-13 Quamba	18.9	1.8	11.4	34.0
A-14 Scandia	23.9	.9	8.4	32.9
Average	21.4	1.3	9.9	33.4

in small quantities, but there is little consistent differentiation among the tills. The lower potassium content in the coarse clays of the Des Moines till may reflect the dilution of the igneous and metamorphic materials by limestone. The lower total exchange capacity for this drift may also reflect the high carbonate content.

In the fine clay fraction (smaller than 0.2 microns) quartz and feldspar are likewise dominant in most of the X-ray analyses, with calcite and dolomite present in some of the Des Moines and Wadena samples. Clay minerals (notably montmorillonite) occur in greater abundance in the fine than in the coarse clay fraction, however. Illite and to a lesser degree kaolinite also occur in the western drifts, but they are also present in the Brainerd till. The potassium percentages and the total exchange capacity for

TABLE 7.—*X-ray and partial chemical analyses of coarse clay fraction (2-0.2 microns).*
+ = abundant − = present

	Qtz.	Fels.	Cal.	Ill.	Mont.	Kaol.	Verm.	Chl.	Aeg.	Dol.	%K	Total Exc. Cap.
DES MOINES TILL												
A-1 Vergas	+	+	+								1.4	16
A-2 Detroit	+		+	−							1.2	18
A-3 Detroit	+	−	+								1.3	18
51-187 Kimball	+	+							?	+		
52-62 Zumbra	+	+							?	+		
WADENA TILL												
A-4 Park Rapids	+	+					−				2.1	38
A-5 Sebeka	+	+	−			+					2.1	27
A-6 Blue Grass	+	+						−			2.1	29
A-7 Verndale	+	+	−	−		−					2.2	25
RAINY TILL												
Brainerd Till												
A-8 Emily	+	+		−			−				2.2	39
A-9 Ft. Ripley	+	+		+		−					2.3	35
Pierz Till												
A-10 Hillman	+	+				−					1.8	39
A-11 Hillman	+	+				−					2.2	44
A-12 Bock	+	+				−					2.3	35
SUPERIOR TILL												
A-13 Quamba	+	+									2.3	37
A-14 Scandia	+	+				−					2.7	31

TABLE 8.—*X-ray and partial chemical analyses of fine clay fraction (<0.2 microns).*
+ = abundant − = present

	Qtz.	Fels.	Cal.	Ill.	Mont.	Kaol.	Verm.	Chl.	Ser.	Aeg.	Dol.	%K	Total Exc. Cap.
DES MOINES TILL													
A-1 Vergas	+				+							1.6	65
A-2 Detroit	−			+	+	−						1.5	64
A-3 Detroit	−		−	+	+							1.6	69
51-187 Kimball	+	+								?	+		
52-76A Cyrus	+	+	+								+		
52-20 Leaf Mtn.	+	+	+										
52-62 Zumbra	+	+									+		
52-67 Hector	+	+	+		?								
WADENA TILL													
A-4 Lark Rapids				+	+	−						1.7	72
A-5 Sebeka	?			?	+							1.7	58
A-6 Blue Grass	−			−	+	+						1.6	65
A-7 Verndale	−			+	+	−						1.7	62
51-229 Blue Grass	+	+	+										
RAINY TILL													
Toimi Area													
51-183 Toimi	+	+											
Brainerd Till													
A-8 Emily				+	+	−						1.3	64
A-9 Ft. Ripley				+	+	−						1.2	54
Pierz Till													
A-10 Hillman	+				+							0.8	53
A-11 Hillman					+							1.1	70
A-12 Bock	−				+							1.2	63
SUPERIOR TILL													
A-13 Quamba	−				+							1.4	63
A-14 Scandia	−				+							1.9	70
51-156 Finlayson	+	+			?								
52-92B Two Harbors	+	+			?								

the western tills in the fine-clay fraction do not differ appreciably from those for the eastern tills—probably a result of the lessened effect of primary carbonate in the fine clay.

As far as the clay-mineral composition is concerned, the above results do not match closely those of Schneider for 30 samples of Superior, Wadena, and Pierz-Brainerd tills in central Minnesota. Schneider (in press) found quartz and feldspar consistently dominant in all tills (along with calcite in the Wadena till), but kaolinite and montmorillonite were most common among the clay minerals, with little trace of illite. Arneman, Khan and McMiller (1958) report principally quartz, feldspar, calcite, cristobalite, and illite in the coarse clay fraction of Des Moines till in Nicollet County in south-central Minnesota; in the fine clay fraction montmorillonite was the only clay mineral present. These analyses for the Des Moines till may be compared with those on similar till in Manitoba obtained by Ehrlich and Rice (1955) who found montmorillonite and illite common in coarse, medium, and fine clay fractions in the till as well as in the soils derived from the till.

Considering the high time costs involved in clay separations, the results of clay-mineral analyses are not particularly useful in differentiating the several tills sampled in Minnesota. Certain conclusions may be taken from the analyses, however.

The strong occurrence of quartz and feldspar in the fine-clay fraction of tills derived from crystalline rocks suggests that processes of glacial abrasion are capable of producing clastic particles of this very small size. In some samples the coarse clay fraction and even the fine clay fraction apparently have no clay minerals. If sufficiently large concentrations of clays without clay minerals could be found (perhaps in some lake deposits), some interesting tests could be made on the relationship between clay composition and certain physical properties such as plasticity, whose values are assumed to be controlled by the clay-mineral composition.

The presence of any clay minerals at all in eastern tills is of some significance, however, inasmuch as the source materials were almost entirely Precambrian igneous and metamorphic rocks of the Canadian Shield, which presumably contain no clay minerals. It may only be inferred that the clay minerals were derived from interglacial weather-

TABLE 9.—*Color compositions of tills*

Sample number and locality	Clark-Maxwell				Munsell
	Black %	Red %	Yellow %	White %	
Des Moines till					
A-1 Vergas	67.8	7.6	17.4	7.2	2.5 Y 5/4
A-2 Detroit	67.0	8.0	16.8	8.2	2.5 Y 5/4
A-3 Detroit	63.1	7.9	18.4	10.6	2.5 Y 5/4
Average	66.0	7.8	17.5	8.7	
Wadena till					
A-4 Park Rapids	66.5	10.3	17.7	5.5	2.5 Y 4/4
A-5 Sebeka	62.8	8.5	19.8	8.9	2.5 Y 5/4
A-6 Blue Grass	62.9	9.4	19.3	8.4	2.5 Y 5/4
A-7 Verndale	61.5	11.5	19.0	8.0	2.5 Y 5/4
Average	63.4	9.9	19.0	7.7	
Brainerd till					
A-8 Emily	69.8	13.4	12.8	4.0	7.5 YR 5/4
A-9 Ft. Ripley	68.8	15.8	12.3	3.1	7.5 YR 5/4
Average	69.3	14.6	12.6	3.5	
Pierz till					
A-10 Hillman	74.0	13.0	9.7	3.3	7.5 YR 4/4
A-11 Hillman	74.1	14.0	8.6	3.3	7.5 YR 4/4
A-12 Bock	74.4	13.8	9.3	2.5	7.5 YR 4/4
Average	74.2	13.6	9.2	3.0	
Superior till					
A-13 Quamba	74.9	16.1	7.2	1.8	5 YR 4/3
A-14 Scandia	74.7	16.1	7.4	1.8	5 YR 4/3
Average	74.8	16.1	7.3	1.8	

ing products or possibly from older sedimentary rocks that may have covered parts of the Canadian Shield. A similar occurrence of clay minerals in Pleistocene tills of the crystalline rock areas of Sweden forced Collini (1956) to a similar conclusion.

Color Composition

Precise color determinations are difficult to make. The most commonly used field method is comparison of the moist sample with the Munsell color chart. This method is generally reliable in distinguishing some of the Minnesota tills where they are relatively pure and confirms the general characterizations of red, brown, gray, buff and other colors. Care must be taken that the moisture content and degree of oxidation are uniform. In overlap regions where the tills may contaminate one another, however, the color distinctions become less prominent (as do other petrographic distinctions), and the use of the Munsell chart does not resolve the delicate but distinct differences in color of two adjacent tills. The most satisfactory field method in areas where color distinctions are tenuous is the collection of small samples in a display tray or box for ready comparison of tills from different localities. Samples may be sprayed with colorless plastic to preserve the moist color.

The Munsell color notations common for the various Minnesota drifts are listed in table 9. Slight differences in determination for a single till sheet may reflect changes in local bedrock as well as the contamination factor mentioned above. The Superior till, for example, is much brighter red in Pine County where the red sandstone bedrock is close at hand..

Table 9 also shows the color composition according to the Clark-Maxwell method of analysis. The Des Moines and Wadena tills have a high percentage of yellow and white compared to the eastern tills. Superior till (red type) has more red than Brainerd and Pierz tills. Pierz till measures darker than Brainerd (more black, less yellow).

CONCLUSIONS

Identification of the various Wisconsin tills in Minnesota depends upon their petrography, their morphology, and their stratigraphic relations. As far as petrogra-

phy goes, the usual field observations of color, texture, and stone content are generally adequate to characterize and identify a till. Laboratory analyses as here presented show the extent of the variations within and between tills.

Color is not easily measured in quantitative terms. The Munsell color chart is usually adequate except where drifts are contaminated and have intermediate colors. The color may be measured more objectively in the laboratory by the Clark-Maxwell method.

Textural analyses as expressed in sand-silt-clay proportions show much local variation, but the field identification of sandy, silty, or clayey till are generally sufficiently precise. Stoniness as determined by the percentage of granules and pebbles is also evident in the field.

Stone counts are perhaps the most useful analyses that can be made of Minnesota tills, for they reveal the source region of the drift and thus the gross direction of ice movement. Such contrasting elements as the presence of limestone in the Wadena and Des Moines tills and their absence in the Rainy and Superior tills (except where contamination exists) are easily seen in the field. Certain indicator stones like Cretaceous shale and Precambrian red sandstone are very useful in identifying drifts. In some cases these occur in such small quantities that they may not appear in a collection of 100 stones. In such cases a normal stone count gives insufficient data, and subjective field observations may be more critical.

Heavy mineral analyses of sand-size particles reveal differences between tills, but the data are less easy to interpret than in the case of stone counts.

Mineralogical analyses of the clay fraction of different tills by X-rays show erratic differences which are not easily interpreted.

REFERENCES

ANDERSON, R. C., 1955, Pebble lithology of the Marseilles Till sheet in northeastern Illinois: Jour Geology, v. 63, p. 228–243.

ARNEMAN, H. F., KHAN, A. B., AND MCMILLER, P. R., 1958, The physical, chemical and mineralogical properties of related Minnesota Prairie Soils: Minnesota Agr. Expt. Station Tech. Bull. 227, 47 p.

COLLINI, B., 1956, Origin and formation of Fennoscandian Quaternary clays: Geol. Fören. Förhandl., v. 78, p. 528–536.

EHRLICH, W. A. AND RICE, H. M., 1955, Postglacial weathering of Mankato till in Manitoba. Jour. Geology, v. 63, p. 572–537.

GELINEAU, W. J., 1959, Pleistocene geology of the Inver Grove and St. Paul SW quadrangles, Minnesota: MS thesis, Univ. of Minnesota, 77 p.

KILMER, V. J., AND ALEXANDER, L. T., 1949, Methods of making mechanical analysis of soils: Soil Sci., v. 68, p. 15–24.

LEVERETT, F., 1932, Quaternary geology of Minnesota and parts of adjacent states: U.S. Geol. Survey Prof. Paper 161, 148 p.

MURRAY, R. C., 1953, The petrology of the Cary and Valders tills of northeastern Wisconsin: Am. Jour. Sci., v. 251, p. 140–155.

MUNSELL, A. H., 1936, A color notation. Munsell Color Company, Baltimore, Maryland.

SCHNEIDER, A. F., 1956, Pleistocene geology of central Minnesota. Geol. Soc. America Guidebook, Minneapolis Meeting, Pt. 3, p. 25–52.

———, (in press) Pleistocene geology of the Randall region, central Minnesota. Minnesota Geol. Survey Bull.

TYNER, E. H., 1940, The use of sodium metaphosphate for dispersion of soils for mechanical analysis: Soil Sci. Amer. Proc., v. 4, p. 106–113.

WINCHELL, N. H. AND UPHAM, W., 1888, Geology of Minnesota. Minnesota Geol. Survey of Nat. Hist., Final Report, v. 2, 695 p.

WRIGHT, H. E., JR., 1955, Valders till in Minnesota: Jour. Geology, v. 63, p. 403–411.

———, 1956, Sequence of glaciation in eastern Minnesota. Geol. Soc. America Guidebook, Minneapolis Meeting, Pt. 3, p. 1–24.

———, AND RUBIN, M., 1957, Radiocarbon dates of Mankato drift in Minnesota. Science, v. 125, p. 1038–1039.

ZUMBERGE, J. H. AND WRIGHT, H. E., JR., 1956, The Cary-Mankato-Valders problem. Geol. Soc. America Guidebook, Minneapolis Meeting, Pt. 3, p. 65–81.

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FIGS. 1–10, DECEMBER, 1959

UNDERWATER GEOLOGY AND ANALYSIS OF RECENT SEDIMENTS OFF THE NORTHWEST FLORIDA COAST[1]

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ABSTRACT

Diving geologists conducted a survey of part of the shallow continental shelf off the west coast of Florida. Sedimentary analysis of samples collected from the Gulf bottom show the sediments to become more coarse and more poorly sorted outward from shore. Ripple marks were found to be predominantly wave formed and to roughly parallel the shore. *Clypeaster sp.* were observed to be destroying the ripple marks in many places. Bedrock which crops out in the area is thought to be the St. Marks Facies of the Tampa Stage.

INTRODUCTION

Heretofore, practically all sea floor samples used in recent sedimentation studies have been collected by the use of devices such as grab samplers which are dropped from a boat. Samples taken in this way cannot always accurately represent the unseen bottom. The grab sampler falls on the collecting site by chance and can easily be influenced by such things as objects on the bottom, marine growth, and current action.

By using SCUBA[2] the geologist is able to move freely along the bottom, take notes, and carefully select his sample location. Trask (1955, p. xviii) stated that "the development of aqua lungs is one of the greatest advances in the study of recent sediments that has come about in the last 15 years." Dill and Shumway (1954, p. 148) and Menard and others (1954, p. 129) have presented reports of geological work done off the California coast by diving geologists.

Large areas of the continental shelf in the Gulf of Mexico could be surveyed easily by the use of SCUBA. Several marine surveys have been conducted in the Gulf of Mexico off the Florida Coast but have been confined largely to the deeper waters offshore. It was the purpose of this investigation to make a study of part of this shallow Gulf Coast shelf by actual observation through the use of SCUBA.

LOCATION OF AREA

The area covered by this report is located offshore from the barrier islands and bars in the vicinity of Carrabelle, Florida, between latitude 29° 35′ N. and 29° 55′N. and between longitude 84° 20′ W. and 84° 45′ W. (fig. 1). It is shown on U.S.C.&G.S. hydrographic chart of Apalachee Bay, number 1261, and U.S.C.&G.S. chart of Apalachicola to Cape San Blas, number 1262.

The continental shelf off this section of Florida is an extension of the Coastal Plain sediments. The surface of the land near shore is composed of a series of beach ridges and loose sands of Pleistocene terraces. Several rivers enter into this section of the Gulf, but only the Apalachicola, which drains part of the Appalachian Mountain system, is carrying a significant amount of sediments.

FIELD PROCEDURE

North-south traverses were run approximately one nautical mile apart outside of the barrier islands. Diving stations were established along these traverses at approximately one mile intervals (fig. 2). Each traverse was ended at such a distance that features on shore could still be seen clearly enough to establish location.

At each station the bottom was described and samples were taken by divers using SCUBA. This technique allowed the investigators to examine the bottom for as large an area as was thought necessary. On the bottom two divers worked closely together but on different aspects of the problem. Notes were taken with grease pencils on plastic sheets. The general characteristics of the sea floor, the type of flora and fauna,

[1] Manuscript received February 18, 1959.
[2] Self contained underwater breathing apparatus.

FIG. 1—Map showing location of area investigated.

the temperature of the water, the orientation of ripple marks, and direction of currents were noted. Ripple marks were measured with a colored plastic ruler for amplitude and wave length. Samples were taken of the unconsolidated sediments and of the bedrock where it was present. Immediately upon returning to the boat, notes taken underwater were rewritten in more detail and samples were put in watertight containers.

ANALYSIS OF SAMPLES

The samples were analyzed and treated statistically in order to correlate grain size with location and water depth. The $CaCO_3$ content was first dissolved in HCl; the insoluble part was then subjected to grain size analysis.

The Tyler Standard Screen Scale with sieve openings increasing in the ratio of the fourth root of two was used. The smallest screen had openings of 0.043 mm. A series of six sieves at a time was run on a Ro-Tap sieve shaker for ten minutes. For purposes of comparison, twelve of these samples (making up two traverses) were also given the sieve analysis without treatment in HCl. It was found that the values derived from the insoluble fraction closely approximate those from the total sample. Cumulative curves were then plotted for each of the samples. Probability paper was used, and cumulative percentages by weight were plotted against grain size in phi units.

The curves from traverses *A*, *E*, *I*, and *O* are representative of those from the entire area. On traverse *A* (fig. 3) the sediment coarsens continuously outward from shore with the exception of sample 9. The last sample is not comparable to the others, however, in that it was taken from a very thin (1–5 cm) layer of fine material overlying bedrock. Because the curves for samples 1, 5, and 7 fall on, or very nearly on, other curves, they have been left out for the sake

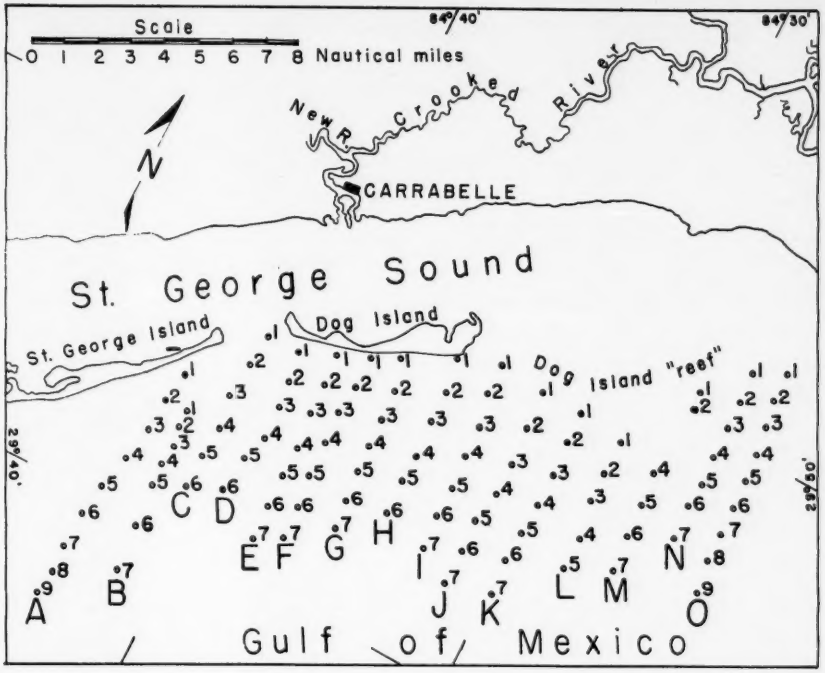

FIG. 2—Map showing location of traverses and stations.

of clarity. The curves for the first five samples of traverse *E* (fig. 4) are closely grouped while samples 6 and 7 show a much coarser material with a loss of fines. The curves for traverse *I* (fig. 5) also show a coarser material in the seaward stations with a loss of fines although the coarsening is not continuous. The curves for traverse *O* (fig. 6) show the seaward stations to have the coarser material but do not show a loss of the fine sizes.

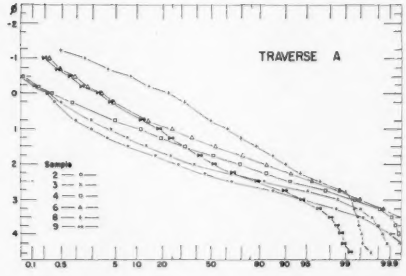

FIG. 3.—Six samples selected from Traverse *A*. Cumulative percent on probability scale plotted against grain size.

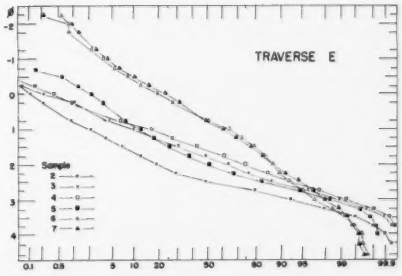

FIG. 4.—Six samples selected from Traverse *E*. Cumulative percent on the probability scale plotted against grain size.

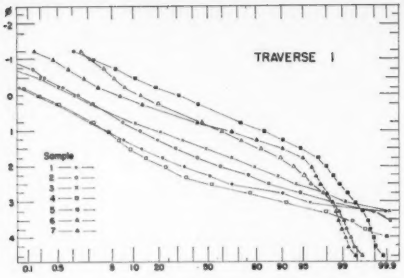

FIG. 5.—Seven samples selected from Traverse *I*. Cumulative percent on the probability scale plotted against grain size.

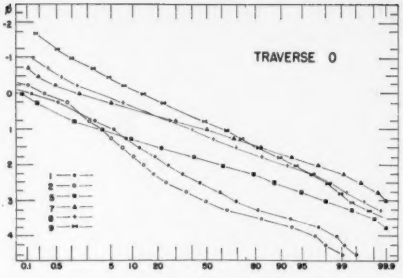

FIG. 6.—Six samples selected from Traverse O. Cumulative percent on the probability scale plotted against grain size.

In general, the curves all show the sediment to become coarser outward from shore. This same correlation was found when the median grain size for each sample was contoured on a map of the area (fig. 7). A channel which runs north-south in the eastern part of the area (fig. 8) seems to be trapping fine material and modifying the general picture.

The sorting coefficient ($So = \sqrt{Q_3/Q_1}$) suggested by Trask was derived for each curve. The sorting coefficient is very limited, however, in that it covers only the central 50 percent of the distribution (Inman, 1952). Percentile deviation in phi units is thought to be a more comprehensive measure. Griffiths (1951, p. 211) used phi percentile deviation based on the P_{90} and P_{10}. Inman (1952, p. 125) recommended that the percentiles P_{95} and P_5 be used. He decided against using the $2\frac{1}{2}$ and $97\frac{1}{2}$ percentiles because of the difficulty of obtaining these diameters for many fine-grained sediments.

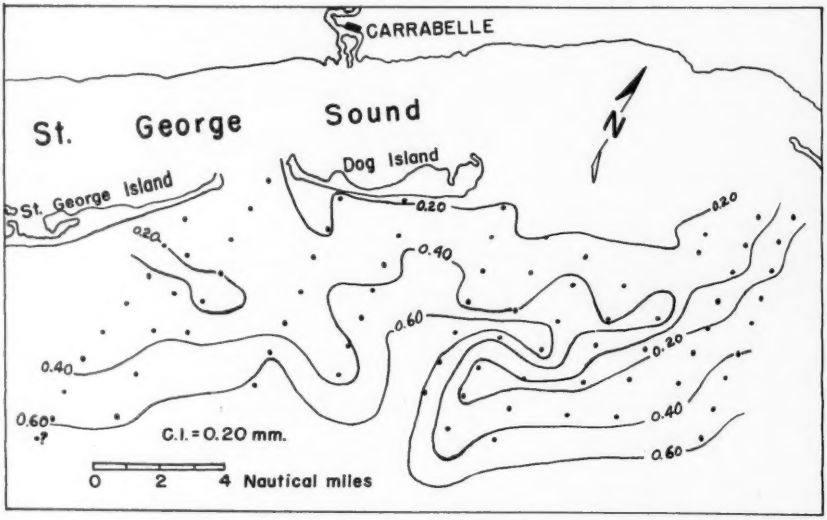

FIG. 7—Distribution of median diameters of quartz sand.

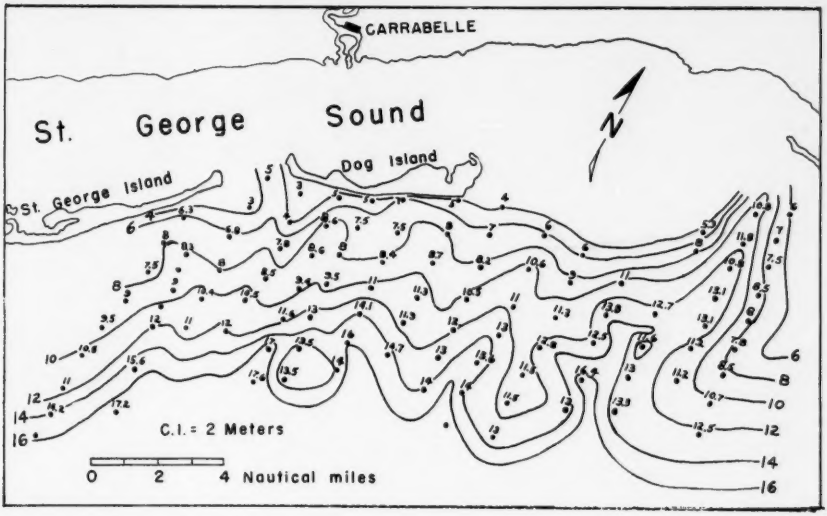

FIG. 8—Water depth.

For the present study it was found that the 1 and 99 percentile diameters could be read from all the cumulative curves plotted. Following the procedure outlined by Tanner (1958), a phi percential deviation based on 98 percent of the sample covers a total of 4.8 standard deviations from the mean and should be written

$$D_{4.8}=\frac{1}{4.8}(P_{99}-P_1).$$

The results of this analysis are shown in table 1.

The samples analyzed were found to be extremely well sorted. The sorting coefficient ranged from 1.17 to 1.60. The $D_{4.8}$ likewise does not vary over a large range. The lowest value was 0.38 and the highest 1.10. The trends shown by the sorting coefficient agree in most cases with those shown by the $D_{4.8}$, with the latter being much more sensitive to changes in the coarse and fine ends of the curve. Both measures of sorting show a general trend of poorer sorting away from shore. This seems to indicate that sorting becomes poorer as median grain size becomes larger.

Griffiths (1951) ran a statistical analysis based on more than twelve hundred samples to determine if a relation exists between Mdϕ and PDϕ. He concluded that between the sizes of 0 and 2.5ϕ sorting becomes poorer as the median diameter becomes larger. A scatter diagram was prepared by plotting Mdϕ against $D_{4.8}$ (fig. 9). Although no definite conclusions can be drawn from figure 9, it does seem to indicate that the coarser grained sediments are poorer sorted. A larger number of samples might give some conclusive evidence.

The divers observed that all the sand near the rock outcrops was coarse grained. At the other stations where this type of sand was found, the proximity of rock was strongly suggested by the high content of limestone fragments and large shell fragments in the sediment. The pieces of rock contained in the sediment are similar in lithology to the rock outcrops found in this area. This type of bottom also supported many of the same types of organisms as found on the rock outcrops. This evidence seems to point to a close relationship between the coarse sand and the bedrock. Gould and Stewart (1955) stated that coarse sand was being weathered from Pleistocene strata exposed on the Gulf

TABLE 1.—*Data for 58 samples which were treated with HCl and the insoluble part subjected to grain size analysis*

Station	Median mm	ϕ	S_0	$D_{4.8}$	Percent $CaCO_3$	Depth in meters
A 1	0.243	2.04	1.26	0.44	2.99	6.3
A 2	0.200	3.32	1.27	0.52	3.53	8.0
A 3	0.228	2.13	1.25	0.54	2.33	7.5
A 4	0.299	1.74	1.28	0.55	2.79	9.0
A 5	0.329	1.60	1.33	0.61	4.96	9.5
A 6	0.366	1.45	1.37	0.69	8.41	10.5
A 7	0.426	1.23	1.41	0.68	16.59	11.0
A 8	0.582	0.78	1.59	0.82	26.62	14.2
A 9	0.258	1.95	1.49	0.98	37.22	15.8
C 1	0.361	1.47	1.21	0.52	1.55	5.0
C 2	0.297	1.75	1.17	0.38	1.52	3.0
C 3	0.253	1.98	1.28	0.58	2.35	6.8
C 4	0.198	2.33	1.30	0.52	3.23	8.0
C 5	0.181	2.46	1.30	0.81	13.39	10.7
C 6	0.342	1.55	1.37	0.68	10.62	11.0
E 1	0.228	2.13	1.22	0.48	1.81	4.3
E 2	0.174	2.52	1.21	0.55	3.17	8.6
E 3	0.291	1.78	1.32	0.58	2.73	8.6
E 4	0.328	1.61	1.31	0.56	5.55	9.4
E 5	0.254	1.98	1.37	0.71	4.91	11.6
E 6	0.598	0.74	1.49	1.06	33.78	17.0
E 7	0.590	0.76	1.60	1.10	25.10	17.6
G 1	0.188	2.41	1.20	0.45	2.70	7.0
G 2	0.316	1.66	1.33	0.52	1.99	7.5
G 3	0.312	1.68	1.34	0.52	3.05	8.4
G 4	0.420	1.25	1.34	0.93	8.05	11.3
G 5	0.484	1.05	1.36	0.71	15.43	14.1
G 6	0.392	1.35	1.45	0.84	25.18	16.0
G 7	0.330	1.60	1.29	0.66	9.07	14.1
I 1	0.215	2.22	1.30	0.55	1.27	4.0
I 2	0.276	1.86	1.31	0.66	3.80	7.0
I 3	0.351	1.51	1.33	0.63	3.64	8.2
I 4	0.181	2.47	1.27	0.62	11.34	10.5
I 5	0.785	0.35	1.37	0.81	17.84	12.0
I 6	0.566	0.82	1.39	1.02	40.44	13.0
I 7	0.568	0.81	1.26	0.92	48.90	14.0
K 1	0.316	1.66	1.26	0.52	3.25	6.0
K 2	0.457	1.13	1.37	0.64	7.10	9.0
K 3	0.426	1.23	1.35	0.79	33.96	11.3
K 4	0.620	0.69	1.70	1.03	23.84	12.8
K 5	0.207	2.27	1.19	1.01	3.52	11.5
K 6	0.233	2.10	1.26	0.49	3.27	11.5
K 7	0.470	1.09	1.36	0.72	17.48	13.0
M 1	0.321	1.64	1.21	0.45	1.21	5.3
M 2	0.254	1.98	1.23	0.52	3.79	8.0
M 4	0.547	0.87	1.48	0.83	18.03	12.7
M 5	0.136	2.88	1.29	0.89	13.40	11.6
M 6	0.289	1.79	1.25	0.48	4.90	13.1
M 7	0.339	1.56	1.29	0.52	5.67	13.3
O 1	0.164	2.61	1.47	0.78	3.89	6.0
O 2	0.123	3.02	1.35	0.86	5.25	7.0
O 3	0.157	2.67	1.37	0.71	3.59	7.5
O 4	0.254	1.98	1.34	0.63	5.36	8.5
O 5	0.272	1.88	1.25	0.51	2.65	8.1
O 6	0.373	1.42	1.23	0.50	3.82	7.8
O 7	0.497	1.01	1.27	0.48	2.25	8.5
O 8	0.435	1.20	1.35	0.63	5.48	10.7
O 9	0.582	0.78	1.42	0.79	11.63	12.5

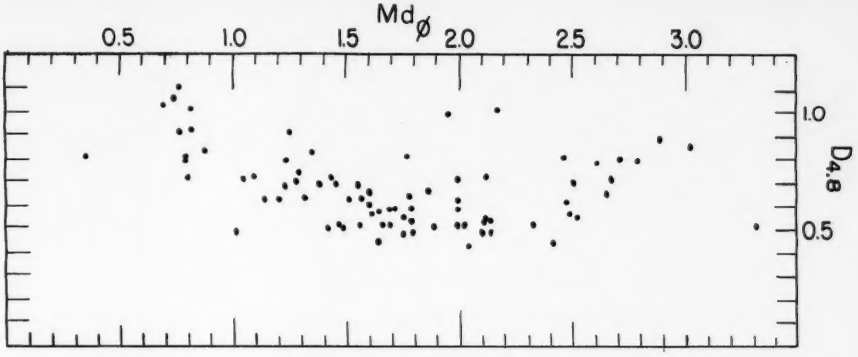

FIG. 9—Scatter diagram with median diameter phi (Md_ϕ) plotted against percentile deviation.

bottom off the west coast of the peninsula of Florida. They also stated that in other places the coarse sand may be lag deposits produced by winnowing of older submerged sediments.

A rock sample from station K-3 was dissolved in HCl and found to be 61.2 percent insoluble material. Most of this material was coarse quartz grains. The sand sample taken from this same location was found to contain 66.04 percent insoluble material. Rock samples from other stations, however, were found to be 84 to 90 percent $CaCO_3$. While sample K-3 would seem to indicate that the sand was weathered from the rock, the other samples do not. It is possible that the coarse quartz sand is a lag deposit resulting from the winnowing of older sediments. Coarse material may have been brought into the area during the Pleistocene when sea level was lower. At that time the rivers could have been transporting coarse sand due to the increased gradient. Processes operating in the area now certainly could not be moving quartz grains of 1 to 4 mm in diameter.

RIPPLE MARKS

All the ripple marks found were oriented more or less parallel to shore. Figure 10 shows the orientation of ripple marks for every station were they were present. Each traverse was run on a different day as indicated by the dates on the figure. Therefore, a wide variety of weather conditions were encountered. For this reason, the ripples could not be expected to have the same orientation.

The ripple marks were predominantly the wave formed symmetrical type, although a few stations near shore had a compound development and showed the influence of current. The symmetrical ripples were of at least two types. One of these was confined entirely to the very coarse sand found in many of the seaward stations. They had an average amplitude of about 8 cm and a wave length of about 70 cm. Very long and straight with a sort of slumped appearance, they gave the impression of old cornfield rows that had been washed down by heavy rains.

Evans (1949) stated that heavy storms will produce fairly persistent ripples in deep water. The action of smaller waves subject ripples to a slow disintegration process during which they become crooked, irregularly spaced, and may have rapid changes in height along the crests. The large ripples described above may have been in such a process of disintegration. Two things seem to support this theory. They were found only at the seaward stations where there was no active wave action on the bottom at the time and they all had the same approximate orientation, although ripples at shallower stations along the same traverse were oriented differently.

The other type of symmetrical ripple was smaller, having a range in amplitude of 1 to

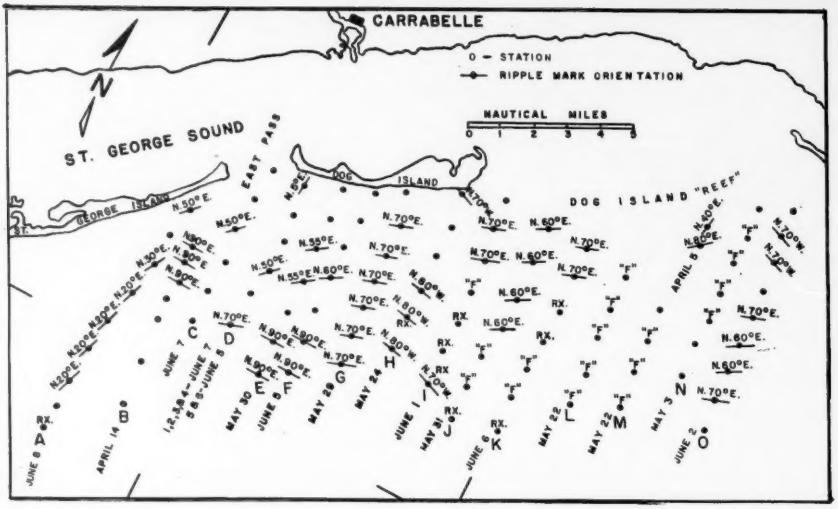

FIG. 10—Orientation of ripple marks plotted. [Stations marked "F" are underlain by fine coherent sand on which no ripples were found. Rx. indicates rock outcrop. The date of each traverse is given.

8 cm and in wave length of 12 to 40 cm. They did not seem to be restricted to any grain size or water depth. They generally appeared to increase in size with water depth, but this did not always hold true.

Echinoids live in large numbers on the sand bottom of this area. *Clypeaster sp.* up to 14 cm in diameter were observed to be flattening ripple marks in many places. They acted much like bullbozer blades as they moved straight through the ripples and left flat trails behind them. It is estimated that they could flatten a well-developed ripple pattern to a smooth sand surface in a few days if other ripples were not formed in the meantime. It seems extremely unlikely that ripple marks formed in such an area would be preverved because of their short existence.

At many of the stations in the eastern part of the area, the bottom was formed by a fine coherent sand (fig. 10). No ripple pattern of any kind was found at these stations. Apparently this sand held together well enough to prevent waves of the area from forming ripples.

LITHIFIED SEDIMENTS

Limestone outcrops were found at nine places ranging from 12 to 17 m in depth. The rock, composed primarily of coral, was fairly hard although it had been badly weathered and thoroughly perforated by small boring organisms. The outcrops were covered with growth of sponge and coral and provided shelter for many types of marine organisms.

Thin sections of a sample taken at station I-6 showed the rock to be a microcoquinoid limestone with abundant *Sorites sp. Sorites* is common throughout the Tampa Stage of the Miocene and reaches maximum size in the calcareous St. Marks Facies (Puri, 1953). The St. Marks Facies of the Tampa Stage underlies the area to the north and could be expected to crop out down dip where the unconsolidated sediments thin to a feather edge.

The bedrock was sampled and described only where it was encountered along the established grid of diving stations. Given more time it would be possible to plot the areal extent of the outcrop and learn a great

deal more about the characteristics of the rock.

SUMMARY

The unconsolidated sediments off Carrabelle, Florida, are composed largely of quartz sand. This sand thins rapidly seaward and in many places several miles from shore forms only a thin cover over bed rock or is absent.

1. All the sediment is extremely well sorted.
   a. Trask's sorting coefficient had a range of 0.43.
   b. The percentile deviation ($D_{4.8}$) had a range of 0.72.
2. The sorting becomes poorer seaward with increase in water depth and increase in median diameter.
3. The $CaCO_3$ content of the sand increases seaward.

Analysis of ripple mark data revealed that the ripples, which were nearly all the wave formed symmetrical type, could be divided into two classes: (a) a large pattern confined to coarse sand and (b) a smaller pattern found in all sizes of sand. All the ripple patterns were oriented roughly parallel to shore.

At many of the stations no ripple pattern was found. This is considered to be caused by the activity of echinoids which flatten the ripples rapidly and to the coherent nature of one sand type.

Consolidated sediments were sampled in nine places. The rock is thought to be the St. Marks Facies of the Tampa Stage (Miocene), because of the lithology, microfauna, and physical position.

ACKNOWLEDGMENTS

This project was under the guidance of Dr. W. F. Tanner of the Florida State University Geology Department and was supported by funds from the Research Council, Florida State University. R. A. Lapp assisted in all phases of the field and laboratory work and is responsible for the photography. Appreciation is expressed to the Florida State Geological Survey and the Florida Board of Conservation for the use of equipment and to the Oceanographic Institute of Florida State University for the use of their boat and facilities.

REFERENCES

DILL, R. F., AND SHUMWAY, GEORGE, 1954, Geologic use of self-contained diving apparatus: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 148–157.

EVANS, O. F., 1949, Ripple marks as an aid in determining depositional environment and rock sequence: Jour. Sedimentary Petrology, v. 19, p. 82–86.

GOULD, H. R., AND STEWART, R. H., 1955, Continental terrace sediments in the northeastern Gulf of Mexico, *in* Finding Ancient Shorelines, Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. no. 3, Tulsa, Oklahoma, p. 2–20.

GRIFFITHS, J. C., 1951, Size versus sorting in some Caribbean sediments: Jour. Geology, v. 59, p. 211–243.

INMAN, D. L., 1952, Measures for describing the size distribution of sediments: Jour. Sedimentary Petrology, v. 22, p. 125–145.

MENARD, H. W., DILL, R. F., HAMILTON, E. L., MOORE, D. G., SHUMWAY, GEO., SILVERMAN, M., AND STEWART, H. B., 1954, Underwater mapping by diving geologists: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 129–147.

PURI, H. S., 1953, Contribution to the study of the Miocene of the Florida panhandle: Florida Geol. Survey Bull., n. 36, 345 p.

TANNER, W. F., 1958, Comparison of phi percentile deviations: Jour. Sedimentary Petrology, v. 28, p. 203–204.

TRASK, P. D., Editor, 1955, Recent marine sediments: a symposium, Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. No. 4, Tulsa, Oklahoma, 736 p.

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FIGS. 1–6, DECEMBER, 1959

NEAR-SHORE STUDIES IN SEDIMENTOLOGY AND MORPHOLOGY ALONG THE FLORIDA PANHANDLE COAST[1]

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ABSTRACT

For the years 1955–1958, a team of geologists from Florida State University investigated the sediments along both sides of the shoreline of part of the coast of the Florida panhandle. These studies have extended as far as 10 miles seaward, where diving techniques were employed, and about an equal distance landward. The bulk of the data so obtained has been concerned with approximate chemical composition (quartz, carbonate, clay), grain size, roundness, heavy mineral content, microfaunal assemblage, ripple marks and related features, and variability of the shallow sea bottom. In the study area, sorting is excellent, quartz is dominant, the grain size increases from the shoreline toward the open gulf, heavy minerals are rare, ripple marks deteriorate more rapidly than had been expected, ripple marks generally trend parallel with the shore, and mild changes in bottom topography are important in the control of sedimentation. Although living organisms having hard parts are numerous, shell fragments are rare in much of the area and a lithified sandstone might well be essentially non-fossiliferous.

INTRODUCTION

The present report summarizes the operations of a shoreline research project at Florida State University for the years 1955 through 1958. The area investigated is situated in the Panhandle of Florida, southwest of Tallahassee (fig. 1). Most of the field work was restricted to a belt approximately 10 miles wide on each side of the shoreline. A preliminary report was presented at the Twentieth International Geological Congress in Mexico City (Tanner, 1956a). The present paper was presented at a meeting of the Southeastern Geological Society, May 20, 1958.

Graduate students who have carried out most of the work include James E. Vause Jr. (1957), William Lapinski (1957), and Richard Lapp, in the years 1955 and 1956; Jesse Milton (1958) and Allan Mullins (1959) in 1957 and 1958; John Waskom (1957; 1958); and Lionel Brenneman (1957; 1958). Many other advanced students assisted at one time or another. Lyman Toulmin, of the geology faculty at Florida State University, directed the microfaunal part of the project.

Funds and equipment for diving operations offshore were furnished, over the four-year period, by the Research Council of Florida State University, the Florida Geological Survey, the Florida Board of Conservation, the Oceanographic Institute of Florida State University, and the Coastal Petroleum Company. This assistance, without which no offshore work would have been possible, is gratefully acknowledged. Captain Leon Langston, of Carrabelle, Florida, served as skipper of the research boat in 1957 and 1958, and contributed greatly to the ease with which the program was carried out.

Seven days of reconnaissance work, for purposes of comparison, were carried out in the Florida Keys (a carbonate environment). In that area, the research boat was furnished and skippered by Captain Herb Alley of Tavernier, Florida.

FIELD METHODS

With the exception of Brenneman, all persons operated wholly or partly in salt water. Brenneman restricted his field work to an area in Tate's Hell Swamp (northwest of Carrabelle, Florida), St. George Island, and St. Joseph spit. He mapped on air photos, and collected samples in all three localities. No special difficulties, other than those of access, impeded his field work.

Waskom collected samples from a variety of environments. Lagoon and offshore samples were obtained by diving. At no

[1] Manuscript received March 9, 1959.

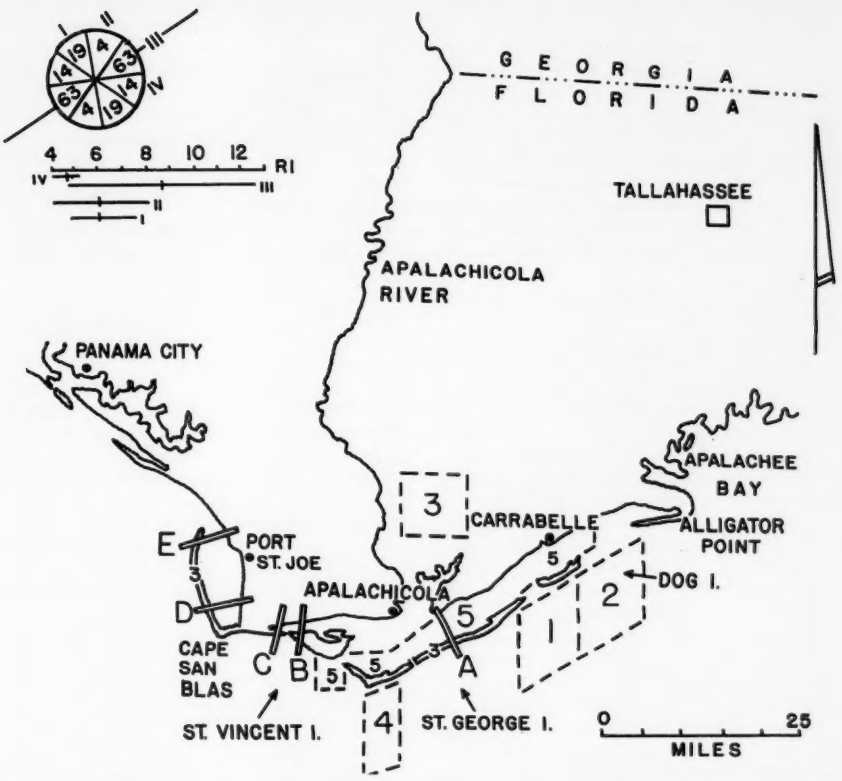

FIG. 1.—Map of the Apalachicola River (i.e., Chattachoochee River) delta area, southwest of Tallahassee, Florida. Numbered areas were studied primarily by the following men: No. 1, Vause and Lapinski; No. 2, Lapp and Lapinski; No. 3 (three locations: on St. George Island; west of Carrabelle; and west of Port St. Joe), Brenneman; No. 4, Milton and Mullins; No. 5, Tanner. Capital letters (A through E) refer to traverses made by Waskom. The compass shows preferred orientations of ripple marks: I, at right angles to the shore line (19% of all observations); III, parallel with the shore line (63%); and II and IV, neither parallel nor at right angles (18%). The lines immediately below the graphic scale show the ripple indices for the same four classes of ripple marks.

sample locality, however, was the water too deep for unaided surface diving. As no submarine work, other than sample collecting, was required, he needed no special equipment.

All other parts of the project involved the use of a seaworthy boat, capable of operating several miles offshore, and fast enough to make a round trip of approximately 100 miles per day. The boats used were the Sea Quest II, a university-owned boat docked at Alligator Harbor; a boat furnished by the Florida Board of Conservation; and the Dolphin and the B. B., out of Carrabelle. The B. B., equipped with recording fathometer, two-way radio telephone, a ladder at the stern, ample deck space, and a fast engine, proved highly satisfactory.

A well-equipped boat, with crew, rents for $60 to $90 per day, depending on distance

travelled, size of boat, and other factors. Transportation expense to and from the coast, plus the cost of compressed air necessary for diving, add $20 to $30 per day. Actual field operating costs averaged almost exactly $100 per day. Efforts to reduce this figure greatly, by using smaller or slower boats, or private boats more distantly based, resulted in an uneconomic increase in the time needed, except where work was carried out within one day's cruising range of Alligator Harbor, where the Sea Quest II was docked.

During off-shore operations, the following were undertaken:

1. Locate the sample point.
2. Describe the bottom, as to rock outcrops, marine organisms, amount of sand cover, and surface markings on the sand (trails, ripple marks, etc.).
3. Observe winds, waves, and currents.
4. Sample the bottom, including lithified material where present.
5. Observe water motion immediately above the bottom. As a general rule, enough organic debris was present to permit this to be done. However, late in the project, water-filled ping-pong balls were prepared, to facilitate this work.
6. In certain localities, additional data were recorded: visibility in the water, salinity, temperature, and current shear.

Samples were later subjected to microfaunal, size, and heavy mineral analysis. In addition, Waskom studied quartz grain roundness.

Sample points were located, on U. S. Coast and Geodetic Survey charts, by means of sextant sightings on landmarks, navigation aids such as buoys, and water depths. Since no traverse was extended more than 10 miles from shore, this was not difficult.

It was imperative that all personnel involved in off-shore operations qualify as both divers and geologists. For the latter reason, only advanced geology majors took part. For the former reason, a diving training school was operated, each winter and spring, under competent instructors.

Field work on the shallow sea floor was carried out with the aid of self-contained underwater breathing apparatus, the use of which has been detailed elsewhere (Dill and Shumway, 1954). Work was rarely extended below 70 feet, and on no occasion below 110 feet.

Experience quickly showed that generally only surface samples (i.e., samples from the rock or sediment surface) could be obtained by divers. In mud or clay environments, plastic tubes can be forced into the sediments a distance of about two feet. No twisting or hammering was sufficient to drive a core tube into loose sand more than a few inches; digging with a small shovel was quicker, if no more effective For this reason, quartz sand was not sampled to depths of more than a few inches. Deeper samples can be obtained by jetting or rotary drilling from a boat, barge or raft.

Twenty minutes was found to be adequate at each sample locality. During this time, a team of at least two divers (for safety reasons) spent 10 or 15 minutes in the water. Most diving was done in water 25 to 70 feet deep. Under these conditions, it was found that about 10 regular dives, plus a few check dives, at intervals of about one mile, plus car and boat travel from Tallahassee, constituted one very strenuous day.

Standard equipment carried by the divers at all times included water depth gauge, waterproof compass, centimeter stick, sample scoop (jar with lid to prevent loss of fines), plastic writing slate, chinagraphic pencil, weight belt, flippers, mask, and breathing apparatus. Other equipment, such as underwater camera, exposure meter, Secchi disk, water sample containers, and current cross, were used at certain sample points.

May and June proved to be ideal months for off-shore work. Water visibility is much better during the winter months, but rough seas make small boat operation hazardous.

Offshore field work, on the shallow sea floor, can be explained, for the non-diving geologist, in fairly simple terms: it is like doing ordinary dry-land field work, on a cold January night, without a moon, during a dust storm, by the light of a flashlight of variable power. The vehicle in the explanation would have to be a helicopter, restricted to flying largely out of sight of the land surface. It lowers the geologist (by rope ladder, perhaps) to the ground, at each sample lo-

cality. He can now see only those materials within the range of his flashlight beam. This might be as much as 60 or 70 feet, or as little as six or seven inches. In the latter instance, he would have to work with his face on the ground; fortunately that is a convenient position for the diver.

Despite the restricted visibility, the geologist-diver quickly learns to orient himself by his compass, criss-cross his area, and jot down his observations. When he returns to the surface, he can copy and expand his notes, and conjure a mental image of what things would look like if sea water did not impede vision.

This description makes the work sound difficult. It *is* difficult. It is also time-consuming and expensive. It is the consensus of those who have taken part, however, that it is a pre-eminently worth-while experience, for the individual geologist, as well as a research technique of considerable importance.

DESCRIPTION OF AREA

The over-all project area has been the coast of Florida. For purposes of actual operations, this has been limited, temporarily, to the coast of panhandle Florida, except for a day in the vicinity of Cedar Keys (west of Ocala, Florida), about seven days in the Florida Keys (extreme southern portion of the state), and about six days on the east coast, between Miami and about Ft. Pierce, Florida. None of the work done on these exploratory trips to other parts of the state is described in the present paper.

For the first two years of investigation (1955 and 1956), team members studied offshore areas from the eastern end of St. George Island to Apalachee Bay (fig. 1), and the narrow sand ridges of Tate's Hell Swamp. For the third year (1957), work was shifted to an area south of the St. George Island light house, and for the fourth year (1958), to St. George Sound. Waskom's assignment, which overlapped several of the others in time, consisted of several single-line traverses, spread from the vicinity of Port St. Joe to the eastern half of St. George Island.

The shoreline in the area is not complicated. The energy level is moderate. The dominant littoral drift is toward the west. A chain of six barriers separates the various sounds and lagoons from the open gulf. Some of these are tied at one end (i.e., at Alligator Point and at Cape San Blas) and therefore are technically spits. East of Dog Island, a 10-mile stretch of lagoon is protected only by a submerged sand bank known locally as Dog Island "reef." The only river draining into the area is the Apalachicola (the Chattahoochee river, of Georgia, described in the poem by Sidney Lanier). The river water empties through a wide, shallow, muddy estuary, into the gulf primarily past the west end of St. George Island, and secondarily through the navigation channel cut through the island, and past the east end of the island. Muddy river water commonly forms a narrow, easily-discerned belt, westward from the navigation cut.

The barriers are, in general, about a mile, or less, wide; the lagoon is approximately five or six miles wide. Since the lagoon is discontinuous, the intracoastal waterway passes through swamps about ten miles north of the shore.

The lagoon-and-barrier complex has been built along the seaward edge of the cuspate delta of the Apalachicola river. Most of the delta surface sediments, outside of modern estuaries, are quartz sand; this fact has been verified over large areas of practically impassable swamp. No wide-spread clay areas, above high tide level, are known, although much clay has been logged in wells drilled in the area.

The wider barrier islands (i.e., St. Vincent Island) and the mainland are marked by beach ridges which are easily visible in the field and on air photos. So far as was determined by Waskom, no extensive clay deposits are exposed in the beach ridge belts. A small amount of wind-driven "blow-out" activity has marred the otherwise almost perfectly straight alignment of the ridges.

The sand-and-clay wedge which makes up the delta rests on Tertiary rocks which dip roughly southward, at an angle of about four feet per mile. Where this rock crops out, south of St. George and Dog Islands and in Apalachee bay, it is a well indurated limestone, probably of Miocene age, perhaps the Tampa. Westward, however, it may grade by facies change into other lithologies, as

does the Miocene limestone exposed in the vicinity of the southwestern corner of Georgia (fig. 1). This fact makes projection of the wave-cut limestone platform, westward under the delta, a hazardous procedure. Wells drilled through the delta penetrated limestone, but at unexpectedly great depths; it is not now known whether the region has been depressed, structurally, or whether the same geometry has been achieved by a facies change.

West of Panama City, other exposures of limestone have been found, in water about 100 feet deep. The strike and dip in that district, however, differ from that found south and southeast of Carrabelle.

The land surface immediately north of the study area is characterized by well-developed terraces generally considered to have had a marine origin (MacNeil, 1949; Lapinski, Revell and Winters, 1958).

AIMS

The main purpose of the project has been to acquire sedimentologic information which might be of value in interpreting quartzose deposits in the stratigraphic column. The work has been restricted to beaches and near-by areas so that, if possible, helpful criteria might be discovered for defining beaches of the past. It has been realized throughout, however, that a beach is an ephemeral line on an undulatory plane, and in most cases probably cannot be recognized once the ocean datum has been altered. For this reason the project has been more concerned with the wedge, or prism, of sediments which make up the beach, rather than with the precise zero contour. The prism of sediments extends, in many instances, for some considerable distance on each side of the actual water line. This line of reasoning leads to the natural suggestion that divers be used, so that sample collecting can be accompanied by a visual inspection of the bottom.

Secondary aims have been to investigate the distribution of heavy minerals (some of them of economic importance) in the study area, to establish environmental ranges for the foraminifera of the area, and to study narrowly-restricted or local problems (i.e., Brenneman, 1958; Waskom, 1958).

It would not be accurate to say that all of the aims have been realized completely. The present report is actually a progress report; most of the persons involved in the project have felt that the work to date has supplied more questions than answers. However, much information has been gained, and, as is commonly the case, the problem now looks more complex than it did formerly.

VARIABILITY OF BOTTOM

Because the area as a whole is relatively simple, it might have been expected that the shallow gulf bottom would also present a simple picture. The bottom exhibits three main types: wave-cut limestone showing karst features; shell hash; and quartz sand. These pass into each other, through various transitions. In general, the shell hash increases seaward, and the bare limestone is more common eastward, but the veneer of quartz sand or shell hash (or both) is commonly so thin that the outline of any one area is irregular. Clay occurs primarily in the lagoons, although the sediments found there are commonly more than 50% quartz sand.

The most variable bottom type is that developed on quartz sand. The most important variants are the following (in no particular order):

1. Admixtures of shell hash.
2. Admixtures of silt.
3. Admixtures of clay.
4. Granule sand.
5. Firm, un-rippled sand.
6. Rippled sand.
7. Echnoid-covered sand.
8. Current-washed sand thickly populated with buried brittle stars (*ophiuroidea*).
9. Sand surface covered with organic "soup," thick with brittle stars, and marked by the characteristics (odor, color, etc.) of reducing environment.

Item 8 occurs where salinities have been reduced slightly by the addition of river water; Item 9, in depressions or "holes" protected on all sides by higher sand banks.

A search has been instituted for: 10. Sediments surrounding a submarine fresh-water spring; although at least one has been located, no work has been done on it yet. It is thought that the faunal assemblage in sediments from Item 10 should be of great interest.

Some of the variants are predictable, in one sense; that is, the environment can be inferred from the sediment, but not vice versa; others, such as Item 5, seem to be completely unpredictable.

REDUCING ENVIRONMENT

The discovery of a reducing environment, even though quite small in area, was surprising (Item 9, above). The best example was found near the mouth of the closed lagoon immediately west of Alligator Point. The lagoon is not only completely closed to the east, but is almost closed to the west by a shallow sand bar cut by a single, narrow, artificial pass. At low tide, the bar is commonly awash, and the pass only about four feet deep. Bottom, in the reducing areas, varies up to almost 30 feet in depth. Less impressive examples were found in other, more open, parts of the lagoon, and in the gulf, where wave action is considerable.

The brittle stars in the reducing environment live above the sand surface, rather than beneath it as they do in Item 8 (above). The situation, for Item 9, appears to be similar to that observed in the Hilltop shale of Oklahoma (Tanner, 1953), where brittle stars are common on the surfaces of certain sandstones overlain by dark shales.

If the sediments of the study area were buried and lithified tomorrow, only fortunate exposures would allow the field geologist to see the thin, spotty, dark layer enclosing the brittle stars. In most exposures no such bed would be found.

Reducing environment was also found in coarse material, quite unprotected from wave attack, in water 20 to 30 feet deep, in Apalachee bay. The sediment consists essentially of coarse to fine shell hash, commonly less than a foot thick. Strong currents flow in the area, making it very difficult for a diver to avoid being swept away.

RIPPLE MARK DURABILITY

The most common bottom dwelling form in the area is the echinoid (*Clypeaster* sp.). This flat animal is so abundant on some parts of the sandy bottom that little or no sand is exposed, except for the thin layer, two or three grains thick, which he carries on his dorsal surface.

In most areas *Clypeaster* is quite mobile. Like a miniature bulldozer, he leaves behind him a more-or-less straight, almost smooth path. These are broken, here and there, by the deeper, narrower trails of gastropods. The action of these organisms is quite sufficient to destroy a ripple mark field in perhaps two days, unless the ripple marks are continuously being regenerated.

SHALLOW WATER RIPPLE MARKS

For much of the area, the median sand grain size is quite consistent (0.3 to 0.5 mm). A plot of ripple mark wave length, against water depth, ignores important information (such as the water surface wave length) but nevertheless reveals an interesting relationship (see fig. 2). For depths from

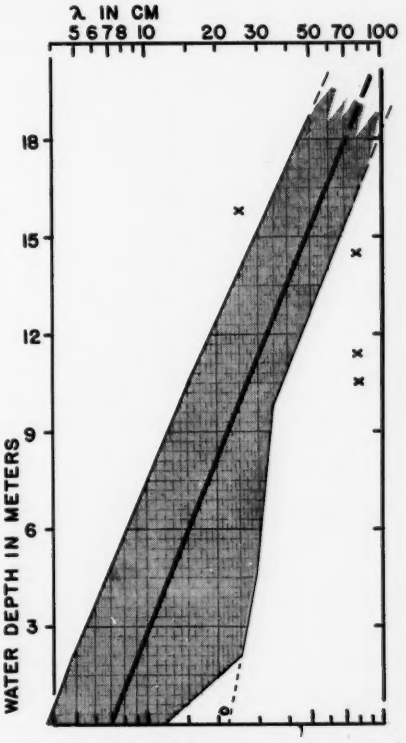

FIG. 2.—Relationship between ripple mark wave length (in cm) and water depth (in meters). All observations fell within the shaded area, except for five scattered points. The heavy black line is an approximate median.

less than one inch to 20 meters (about 65 feet) about100 ripple measurements yielded what appears to be a straight-line semi-log curve, which can be expressed as $h_m = 18 \log \lambda_{cm} - 15.3$.

FLAT-TOPPED RIPPLE MARKS

These aberrant forms, found only in water about two inches, or less, deep, appear to be quite common. Their wave-length is generally between five and 12 cm, and averages about 10.5 mm. A simple example has been described, and compared with flat-topped ripple marks found in the rock column (Tanner, 1958a); earlier descriptions have been published by Wegner (1932), and Rücklin (1934, 1954).

In many instances, barchan-like ripple marks are planed during falling tide, leaving only crescent-shaped troughs or depressions marking an otherwise flat sand surface. In some instances, small ripple marks develop on the flat upper surfaces of larger ones; generally the two sets are not parallel with each other.

RIPPLE MARK ORIENTATION

Ripple mark trends were observed in terms of compass bearings. For later study, however, these data were recalculated in terms of parallelism with the shoreline. Compass data were arranged in classes:

Class I. Ripples essentially at right angles to the shore.
Class II. Rotated, clock-wise, 45°.
Class III. Rotated 90°; hence essentially parallel with the shore.
Class IV. Rotated 135°.

It was found (fig. 1) that ripple mark trends occupy the classes as follows:

I. 19%.
II. 4%.
III. 63%.
IV. 14%.

These data are for off-shore ripple marks, and do not include any trends from inside the lagoons.

RIPPLE MARK INDEX

A ripple index (RI) was computed as (wavelength)/(amplitude). The limiting values obtained for RI were 1.5 and 17.5. Two percent were greater than RI = 13, and 23% were less than RI = 4. All of the values below RI = 4 were found in water only a foot or so deep.

RI was determined for each of the orientation classes identified above. These data, presented in fig. 1, can be summarized as follows:

I. Average RI = 6.15, standard deviation = 1.41.
II. Average RI = 6.0, standard deviation = 2.1.
III. Average RI = 8.68, standard deviation = 4.0.
IV. Average RI = 4.66, standard deviation = 0.577.

It can be seen that the most consistent group of ripple indices were obtained from Orientation IV, and the least consistent group from Orientation III. Ripple marks from III include those formed by wave action during both fair and stormy weather, and hence can be expected to show more variation. These data do not include any RI less than 4.

RIPPLE SYMMETRY INDEX

A ripple symmetry index (RSI) was obtained by calculating the ratio between the map width of the steep face, and the map width of the gentle face. These two widths were measured so that they totalled to the ripple wave length ($a+b=\lambda$; RSI $= a/b$, with a so chosen that RSI exceeded unity).

In this system, a perfect wave-formed ripple has RSI = 1, whereas a current ripple has RSI appreciably greater than 1. Because of visibility handicaps, it was not possible, in many instances, to measure both a and b; hence RSI was not invariably calculated. About 50% of the ripple marks which were measured yielded RSI = 1. Other values ranged up to 8. High values for asymmetry (4 and above) were obtained from passes, or lagoonal locations where swift currents were running. Ripple marks observed as much as several miles from shore generally had RSI values at or very close to 1. Wave-formed ripple marks (RSI = 1) were found in water as deep as 20 meters (about 65 feet).

MOUNDS AND PITS

Many small features, a few inches or a few feet across, have been observed in the course of diving operations. Mounds, much like miniature volcanic cones a few inches across, have been studied in the esturaries and off of Dog Island. These mounds were built by the unidentified organisms which inhabited the centrally-located burrow. The chief characteristics of the mounds are: nearly circular outline, small crater at top or center, gentle outward slope, clean white color of the sand compared with similar sand outside the mounds. Efforts to capture the burrowing organisms netted nothing.

Pits, a few inches deep and a foot or two across, were seen in several places on the lagoon floor. Apparently no organisms were associated with the pits at the time of observation.

LOW-TIDE DELTAS

At low tide, water draining from the beach sands may cut a system of narrow, V-shaped, parallel valleys, an inch deep, and about two feet long. The sand removed, in the process of cutting these valleys, may be deposited in the form of fans, or deltas, at the low-tide water-line (fig. 3). Such low-tide deltas have been observed in the vicinity of Alligator Point. They were spaced, along the beach, at intervals of 5 to 10 feet. Each delta covered an area of three or four square feet. The top surface of each was marked by a typical distributary pattern.

Ripple mark troughs, in the vicinity of the low-tide deltas, are commonly partly filled with sand transported across the deltas. The result may be flat-*bottomed* ripple marks. These grade into obscured ripple marks, close to the delta front, where the sand filling has nearly reached, or even exceeded, the ripple crest.

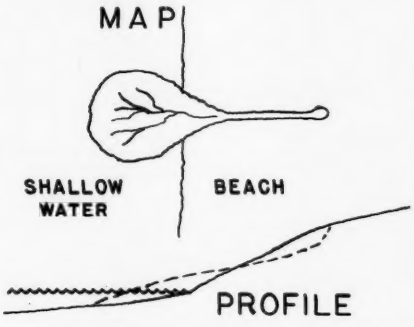

FIG. 3.—Map and profile of a low-tide delta, found along the beach. The delta is 10 to 20 inches across.

QUARTZ FRACTION

With certain exceptions, given in more detail in another paragraph, the quartz grains in the area increase in diameter in a seaward direction. Since sampling was not extended more than 10 miles seaward, it is not known how far this tendency continues. In the relatively featureless area south of Dog Island, however, median diameters increase from 0.10 to 0.20 mm, close to shore, and 0.20 to 0.30 mm along the beach, outward to about 0.60 mm, at an average distance of about six miles from shore. The coarsest median diameter found landward of the beach was 0.42 mm (average median) from the Ochlockonee River.

Sorting became poorer, seaward, whether expressed in terms of the Trask coefficient, $S\phi$, or phi statistics. The phi deviation measure, D_k (which approximates σ; fig. 6; Tanner, 1958b), varied from about 0.50, near the beach, to about 0.90 along the seaward edge of the study area (using $D_{4.8}$). $S\phi$ ranged from about 1.20, near the beach, to about 1.50 along the seaward edge.

Where obvious bottom topographic irregularities occur, median diameter and sorting behave somewhat differently. Although the over-all seaward trend is as given above, topography exerts a clear influence on both parameters. With a few exceptions, the coarser median diameters represent the topographic hollows (deeper water), and the finer median diameters represent the bars (shoaler water).

An attempt was made, using median diameter and D_k (both in phi units), to characterize the quartz fraction of the various environments. The plot (fig. 4) which was constructed includes median diameters (in phi units) from 0.40 to 2.56, and D_k (phi percentile deviation) from 0.27 to 1.10. It was found that two sample sets (those representing open gulf, and river sands) are, relatively, coarse and poorly sorted. All other sample sets (beaches, dunes, marshes,

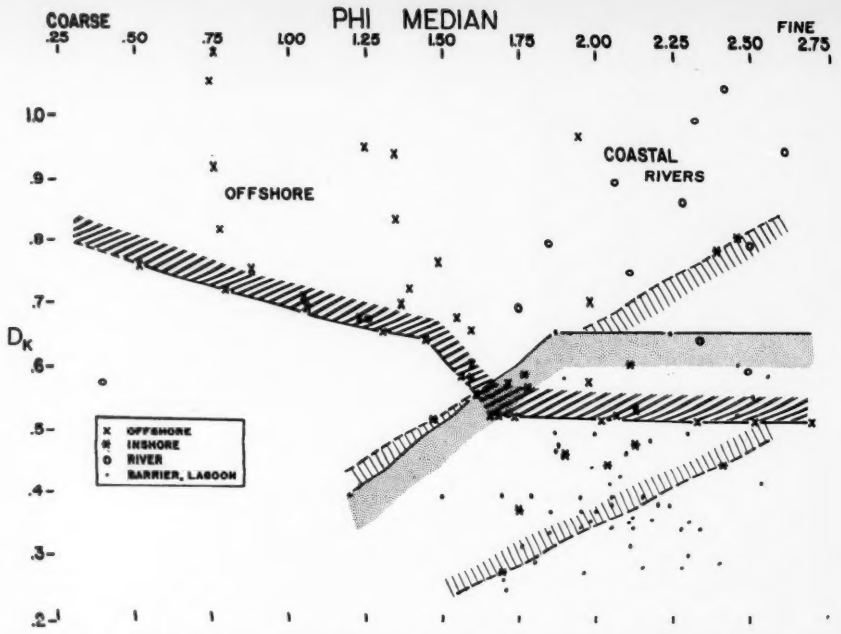

FIG. 4.—Phi deviation measure (D_k) plotted against phi median diameter, for representative samples. The stippled margin marks the limits of barrier, beach and lagoon sediment plots. The double-line shading marks the limits of offshore sediment plots (i.e., one mile, or more, from the beach). The single line shading denotes the limits of plots for samples taken between the beach and the one mile mark. It will be noted that the finest, best sorted sediments were collected from the barrier, beach and lagoon environments; the coarsest sediments with the poorest sorting from offshore; and the finest sediments, with poorest sorting, from coastal rivers and offshore areas.

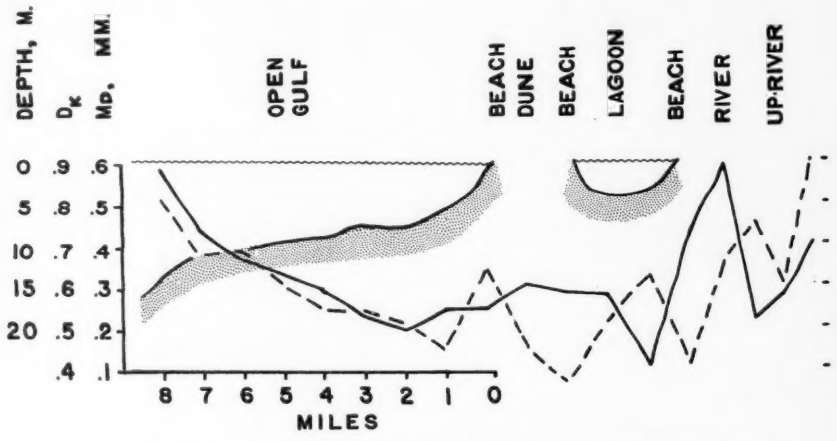

FIG. 5.—Diagrammatic profile of water depth (stippled), sorting (D_k; dashed line), and median diameter (in mm; solid line).

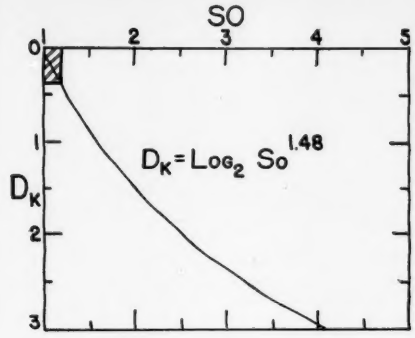

FIG. 6.—Chart for converting, approximately, D_k to *So* (Tanner, 1958b). The shaded area represents those measurements obtainable only with great care, if at all (Tanner, 1956b).

and lagoons) are fine and well sorted. A diagrammatic profile across the area is given in fig. 5.

A plot of data, according to Passega (1957) showed that barrier island, dune, beach, and lagoon samples fall in his "beach pattern."

ROUNDNESS

Waskom (1958) studied the roundness of quartz grains collected along five different profiles, each of which extended from gulf waters, across the barrier island and lagoon, and onto the mainland. He labelled the various environments represented as follows: off-shore, open swash, dune, beach ridge, marsh, protected swash, lagoon, and river. His study was unique in that he examined a relatively wide range of sand, and coarse silt, sizes: those grains coming to rest on the 0.175, 0.088, and 0.043 mm screens (1/6, 1/12, and 1/24th mm).

The two coarser sizes (0.175 and 0.088 mm) showed few differences between them, with a single exception: in the open swash zone, the finer of the two was also more rounded. The finer size (0.043 mm) was much less rounded at all places except in the river environment, where it was slightly less rounded.

Waskom also found that environments in the study area could not be distinguished, positively, on the basis of roundness values alone. The following differences did appear, however (using C for 0.175 mm, M for 0.088 mm, and F for 0.043 mm):

C, moderate roundness; M, high; F, low: open swash.
All three low: marsh or protected swash.
All three high: beach ridge.
All three clustered closely: river.
C and M, moderate: F, low: lagoon, or off-shore, or dune.

HEAVY MINERALS

No single sample yielded as much as two percent, by weight, of heavy minerals. In the eastern part of the area heavy minerals were either completely absent, or present only in trace quantities. The greatest concentration was found south of the west end of St. George Island. Magnetite-and-ilmenite, epidote and kyanite were the most abundant heavy minerals found. Staurolite, leucoxene, rutile and hornblende contributed more than five per cent, each, to the total.

The heavy mineral suite is essentially the same as that reported by Cazeau (1956) from the lower Chattahoochee river.

MICROFAUNA

Lapinski (1957) and Milton (1958) were responsible for description of foraminifera from part of the region. Lapinski worked the area south of Dog Island, and Milton south of the western end of St. George Island. The two areas differ primarily in that much Apalachicola River water is introduced between them, and the dominant littoral drift is such that the Dog Island area is only slightly affected, but the St. George Island area greatly affected.

Elphidium gunteri and *Quinqueloculina lamarkiana* characterize the St. George Island area, and *Discorbis concinnus* and *Streblus beccarii* mark the Dog Island area. These four species can be used to identify samples taken from the two areas.

Typical deep-water forms, reported from other parts of the Gulf of Mexico, which occur in shallow water in the study area include: *Anomalina io, Cibicides deprimus, Uvigerina bellula, U. flintii,* and *Valvulineria sp.*

Ammobaculites exiguus is one of the few species which is generally common in the shoaler areas.

REFERENCES

BRENNEMAN, L., 1957, Preliminary sedimentary study of certain sand bodies in the Apalachicola delta. Master of Science thesis, Florida State University.

BRENNEMAN, L., AND TANNER, W. F., 1958, Possible abandoned barrier islands in panhandle Florida: Journal of Sedimentary Petrology, v. 28, p. 342–344.

CAZEAU, C. J., 1955, An analysis of some Chattahoochee River sediments. Master of Science thesis. Florida State University.

DILL, R. F., AND SHUMWAY, G., 1954, Geologic use of self-contained diving apparatus: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 148–157.

LAPINSKI, W. J., 1957, The distribution of Foraminifera off part of the Florida panhandle coast. Master of Science thesis, Florida State University.

LAPINSKI, W. J., REVELL, S. R., AND WINTERS, S. S., 1958, Sedimentary analysis of terrace deposits in panhandle Florida: Jour. Sedimentary Petrology, v. 28, p. 75–92.

MACNEIL, F. S., 1949, Pleistocene shorelines in Florida and Georgia: U. S. Geol. Survey Prof. Paper 221-F, p. 50–107.

MENARD, H. W., DILL, R. F., HAMILTON, E. L., MOORE, D. G., SHUMWAY, G., SILVERMAN, M., AND HARRIS, H. B., 1954, Underwater mapping by diving geologists: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 129–147.

MILTON, J. W., 1958, The distribution of Recent Foraminifera south of St. George Island Florida., Master of Science thesis, Florida State University.

MULLINS, A. T., 1959, A study of marine sediments from the Gulf of Mexico. Master of Science thesis, Florida State University.

PASSEGA, R., 1957, Texture as characteristic of clastic deposition: Am. Assoc. Petroleum Geologists Bull., v. 41, p. 1952–1984.

RÜCKLIN, H., 1934, Über Wurmspuren im Voltziensandstein des Nordsaargebietes; Badische Geologische Abhandlungen, v. 6, p. 81–100.

———, 1954, Die Grenzschichten Buntsandstein/Muschelkalk im Saarland—ein fossiles Watt: Jarhresberichte und Mitteilungen des Oberrheinischen Geologischen Vereins, new series v. 35, p. 26–42.

SHUMWAY, G., 1955, Compass-ir.clinometer for underwater outcrop mapping: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 1403–1404.

TANNER, W. F., 1953, Facies indicators in the upper Pennsylvanian of Seminole County, Oklahoma: Jour. Sedimentary Petrology, v. 23, p. 220–228.

———, 1956a, Preliminary report on results of near-shore diving research program at Florida State University: XX International Geological Congress, Mexico City. In press.

———, 1956b, Lower limits to the *So* coefficient: Jour. Sedimentary Petrology, v. 26, p. 158–159.

———, 1958a, An occurrence of flat-topped ripple marks: Jour. Sedimentary Petrology, v. 28, p. 95–96.

———, 1958b, Comparison of phi percentile deviations: Jour. Sedimentary Petrology, v. 28, p. 203–204.

———, 1958c, The zig-zag nature of type I and type IV curves: Jour. Sedimentary Petrology, v. 28, p. 372–375.

———, 1958d, The equilibrium beach: Am. Geophys. Union Trans., v. 39, p. 889–891.

VAUSE, J. E., 1957, Submarine geomorphic and sedimentological investigations off part of the Florida panhandle coast. Master of Science thesis, Florida State University.

WASKOM, J. D., 1957, Quartz grain roundness as an indicator of depositional environments of part of the coast of panhandle Florida. Master of Science thesis, Florida State University.

———, 1958, Roundness as an indicator of environment along the coast of panhandle Florida: Jour. Sedimentary Petrology, v. 28, p. 351–360.

WEGNER, TH., 1932, Unter Gezeiteneinwirkung entstandene Wellenfurchen: Centralblatt für Mineralogie, Geologie und Paläontologie, Stuttgart, Abteiling B, p. 31–34.

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FIGS. 1–6, DECEMBER, 1959

THE "SORTING OUT" OF GEOLOGICAL VARIABLES ILLUSTRATED BY REGRESSION ANALYSIS OF FACTORS CONTROLLING BEACH FIRMNESS[1]

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ABSTRACT

Observations on beach firmness suggest that it is dependent on moisture content, average particle size, degree of sand sorting, and degree of packing of the beach sand. A method of multiple linear regression that may be extended to the non-linear case is applied to the problem of "sorting out" empirically the relative effects of the controlling properties. The analysis involves several stages, in which the controlling factors are treated one at a time, two at a time, and so on, to allow for interrelations among the controlling factors themselves. A detailed example is presented for illustration of the method, and an Appendix to the paper includes some theory as well as a summary of the IBM 650 program used in this study.

A summary of several sets of data suggests that moisture content is the dominant control of firmness, with average grain size more important than degree of sand sorting. Some limitations in present data on sand packing hinder evaluation of this factor, but it appears to be less important than moisture content.

INTRODUCTION

In most sedimentary studies it is apparent that more than one controlling factor exerts an influence on the properties of a sedimentary deposit. Among questions that arise are the following: How many controlling factors are involved in the process? Are these factors interrelated in some way? For a given set of factors, which one or more are most important in controlling the phenomenon under study? Are these same factors most important under all environmental conditions, or may their relative importance vary from one situation, or one time, to another?

Despite the complexity of most sedimentary processes when considered in detail, it is probably true that in many circumstances some one or a few factors exert most control over the dependent variable. These may be thought of as "first order" independent variables in contrast to others that apparently exert only minor control, and yet are present in sufficient degree to add to the total variability of the phenomenon being observed. How may the first order independent variables be "sorted out" from the set of variables? To what degree do these few variables "explain" the total variability of the dependent variable, and what is the pattern of the "unexplained" variations?

The problem selected for analysis here involves the firmness of a beach as a function of several properties of beach sand. Qualitative study of the ease of walking on a beach indicates that damp sand is firmer than dry sand, and that fine dry sand is somewhat firmer than coarse dry sand. As dampness increases the firmness also increases, sometimes to a maximum value at some intermediate moisture content, but under some circumstances the firmness continues to increase virtually to the water line. On a developing beach foreshore where sand is being deposited, the wet sand may be quite soft; on a more stable foreshore and particularly on an eroding foreshore, firmness may be greatest in the fairly wet sand near the water's edge.

It seems apparent from these relations that the degree of packing of the sand, as well as moisture content, may exert some control on firmness. Sand particle size is also a factor, however, and it is sometimes difficult to decide whether packing or particle size is more important in modifying the effect of moisture content. In addition, it may

[1] Based on a paper presented at the 33rd Annual Meeting of the Society of Economic Paleontologists and Mineralogists, Dallas, Texas, March, 1959.

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be inferred that the degree of sorting of the sand may be a factor in firmness. Whether grain shape and grain orientation are important is difficult to judge by qualitative observation, but in a complete study these variables could be included.

Beach firmness may be measured in various ways. If firmness is considered to be an expression of the strength of the sand, it would appear to depend mainly on lateral confining pressure and on the angle of internal friction in the sand (Taylor, 1948, p. 553). The angle is dependent on the degree of packing of the sand (expressed as porosity, void ratio, or dry bulk density) and on grain size. The lateral confining pressure is affected by moisture content, which may increase the effective stress in slightly damp sands, or decrease it in saturated sands.

Evaluation of the factors just described may be approached effectively in a laboratory study, in which selected variables can be held constant while the effects of changes in others are examined. For purposes of the present paper, however, the problem of firmness can be used as an example of the empirical "sorting out" of a number of variables under more usual sedimentary field conditions where all or most of the variables may be expected to vary simultaneously.

PLAN OF ANALYSIS

In stuying the effects of several independent variables simultaneously, common procedure is to assume that the relations among the variables are linear. This is not a necessary assumption in the present method, but for the example illustrated here it is not extreme.

In the first stage of analysis the linear relation between the dependent variable (firmness) and the independent variables is examined one at a time. This stage commonly permits identification of the single independent variable that exerts the greatest apparent control on the dependent variable. In the second stage of analysis the relation between beach firmness and all possible pairs of independent variables is examined. This stage commonly permits identification of the second most important independent variable. For identifying the third most important independent variable, or for ranking the independent variables in their apparent order of importance, more than one technique may be used, as developed briefly in the Appendix.

The plan of analysis described here can be routinized for the IBM 650 or for other high speed computers. Essentially it consists in the machine first computing by least squares methods the linear coefficients of the line of regression of beach firmness on each independent variable. A function of the type

$$X_0' = a + bX_r \tag{1}$$

is fitted to the data, where X_0' is the computed value of the dependent variable X_0 on the regression line and X_r represents any one of the independent variables. The coefficients a and b represent respectively the X_0 intercept and the slope of the straight line.

In the second stage of analysis the machine takes the independent variables in pairs, and computes the linear coefficients of the plane of regression of beach firmness on all possible pairs. This extends equation (1) to the following:

$$X_0' = a + bX_r + cX_s \tag{2}$$

where X_0' is the computed value of X_0 on the regression plane, and X_r and X_s represent pairs of the independent variables. The coefficients a, b, and c represent respectively the X_0 intercept and the slope of the plane associated with X_r and X_s. The coefficients change in value as the analysis includes additional variables.

The third and later stages of this linear analysis involve adding an additional independent variable to the right of equation (2) for each stage, and fitting linear regression functions to all possible triplets, quadruplets, etc., of the independent variables. The present example includes only the first two stages, which can be shown graphically, but an IBM 650 program for several stages is described in the Appendix.

In all stages of analysis the reduction in the sum of squares of the dependent variable is computed for all lines, planes, or surfaces fitted to the observed data to provide a criterion for estimating the relative importance of the independent variables in controlling the behavior of the dependent variable. The sums of squares are defined in the

TABLE 1.—*Beach data, Wilmette, Illinois*

Sample	Geometric mean diameter, mm.	Phi standard deviation	Moisture content, %	Porosity, %	Ball penetrability
1	0.41	0.77	3.3	44.2	6.0
2	.36	.80	3.3	43.8	7.0
3	.45	1.07	3.0	42.0	6.0
4	.27	.53	2.8	43.5	7.0
5	.23	.33	4.3	42.8	5.0
6	.30	.41	3.1	49.2	5.0
7	.30	.52	4.4	43.0	5.0
8	.38	.86	3.6	40.6	4.0
9	.52	1.13	2.6	39.2	6.0
10	.30	.48	2.8	42.7	6.0
11	.28	.41	2.7	42.0	5.0
12	.25	.33	2.8	41.8	3.0
13	.60	.87	3.3	40.1	9.0
14	.42	.80	3.3	43.8	4.0
15	.48	.72	3.0	44.8	8.0
16	.28	.53	4.1	45.8	7.0
17	.28	.53	3.7	41.8	6.0
18	.29	.53	3.8	43.6	6.0
19	.21	.32	24.3	42.9	1.0
20	.22	.37	24.3	42.1	1.0
21	.25	.37	23.0	41.6	1.0
22	.22	.32	21.3	42.1	2.0
23	.38	.83	17.8	43.8	1.0
24	.23	.37	21.6	42.8	2.0

Appendix. Assumptions involved in using the sum of squares reduction as a criterion are mentioned in a later section of this text.

BEACH FIRMNESS AT WILMETTE, ILLINOIS

The data analyzed for illustrative purposes here represent a set of 24 sand samples collected from the public beach at Wilmette, Illinois, about 15 miles north of Chicago. For a number of years the writer and his students, in collaboration with E. C. Dapples, have collected samples of beach sand for study of areal variations in beach properties. With the recent establishment of an IBM 650 Computing Center at Northwestern University it became possible to review earlier data in terms of the present approach without the prohibitive time requirements of hand computation.

The data used here were obtained in 1949, and they have some limitations inasmuch as the original study was not designed for the present analysis. Nevertheless the example has some interesting aspects. Beach firmness was measured by dropping a steel ball of approximately 2 inches diameter from a fixed height and measuring the depth of penetration. A sample of sand was then collected immediately adjacent to the ball test by rotating a half-pint cylinder into the sand with as little disturbance of the deposit as possible. The samples were weighed directly in their containers, dried, and reweighed. The moisture content was computed from damp and dry weight, and an estimate of sand porosity was made from the dry weight and sample volume in terms of the specific gravity of the sand grains. Porosity was used as a measure of sand packing. A subsample of the sand was sieved to determine the mean grain size and degree of sorting.

Table 1 lists the sample data. Ball penetration (variable X_0) is taken as the dependent variable. It is a measure of beach softness, but in the context ball penetration is used as representing beach firmness, with the understanding that the greatest firmness is associated with the least penetration. The geometric mean grain size (X_1), phi standard deviation (X_2), moisture content (X_3), and porosity (X_4) are taken as the independent variables. The grain size properties and moisture measurements satisfy usual standards of accuracy, but the porosity estimates are only approximate owing to the practical difficulty of avoiding

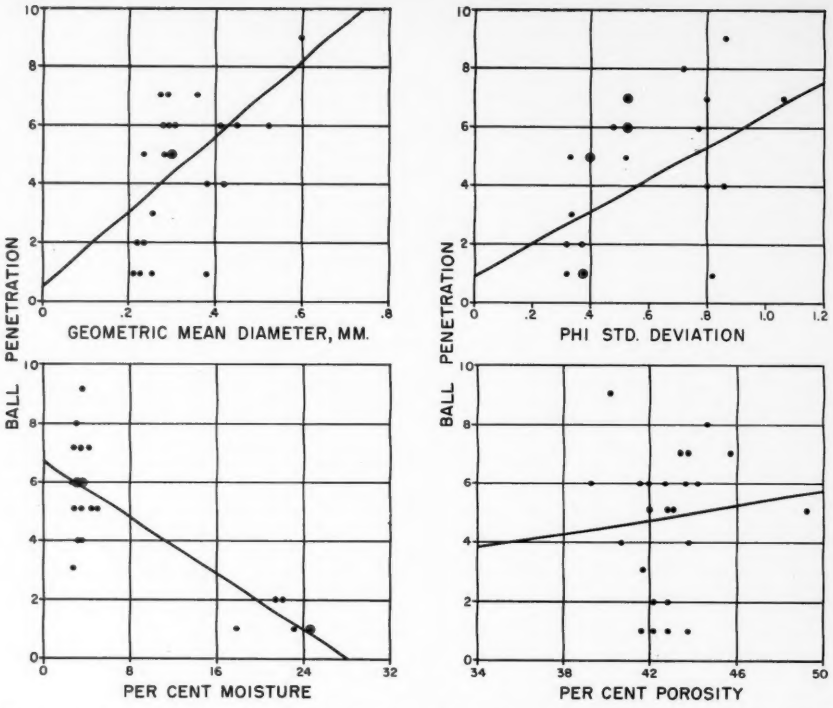

FIG. 1.—Scatter diagrams and regression lines for Wilmette beach example. Data in tables 1 and 2

grain disturbance during collection of the samples. Similarly, the ball penetration data are approximate, and for purposes of analysis were rounded to the nearest $\frac{1}{10}$ diameter.

The example was chosen in part because it represents a situation in which beach firmness increased continuously from dry to rather wet sand. Although the actual sand samples had either a low or a high moisture content, as shown in table 1, additional ball tests taken at fairly closely spaced positions on the foreshore showed no tendency for increasing penetration as the sand became noticeably damper. Unfortunately no sand samples were taken at these intermediate points, but the ball tests showed that firmness increased steadily from the upper part of the foreshore to the water's edge.

The data in table 1 were punched on IBM cards and run through the first stage of analysis. Figure 1 shows the least squares straight lines drawn on scatter diagrams of firmness plotted against each independent variable in turn. Table 2 summarizes the first stage, with the linear coefficients a and b for each straight line, as in equation (1). The last column of the table shows the per cent reduction in the sum of squares of

TABLE 2.—*Summary of first stage of analysis*

Pair of variables	Linear coefficients		Reduction in sum of squares of X_0
	a	b	
X_0, X_1	0.376	13.146	33.92%
X_0, X_2	2.129	4.359	20.48
X_0, X_3	6.600	−0.236	69.79
X_0, X_4	−0.322	0.117	0.96

TABLE 3.—*Summary of second stage of analysis*

Pair of independent variables	Coefficients[1]			Reduction in sums of squares of X_0
	a	b	c	
X_1, X_2	0.121	18.904	−2.776	35.72%
X_1, X_3	4.603	5.286	−0.204	74.00
X_1, X_4	−12.140	−14.315	0.283	39.26
X_2, X_3	5.887	1.026	−0.223	70.71
X_2, X_4	− 9.994	4.930	0.275	25.42
X_3, X_4	6.494	− 0.236	−0.002	69.81

[1] The coefficients are given in the same order as the variables in column 1. Thus, the first equation is $X_0' = 0.121 + 18.904X_1 - 2.776X_2$.

firmness associated with each linear relation. This reduction in the sum of squares is used as a criterion for the "strength" of the linear relation, and the independent variable that most greatly reduces the sum of squares of X_0 is taken as the single strongest independent variable in the set.

As the graphs of figure 1 show, the assumption of linear relations (if any) is not extreme for this example. Table 2 indicates that the moisture content, X_3, reduces the sum of squares of firmness by 69.79%, and it is accordingly taken as the single most important independent variable in the set. In part the large reduction in the sum of squares due to moisture results from clustering of the observed points at low and high values. Such clustering tends to produce a strong linear relation, but in the light of the evidence cited in a preceding paragraph for a continuous increase of firmness to the water line, it is believed that additional sand samples would have fallen along essentially the same linear trend.

In the second stage the independent variables are taken two at a time, as mentioned, and the coefficients a, b, and c are computed in accordance with equation (2), as well as the total reduction in the sum of squares of X_0 attributable to each pair. Table 3 presents the results. It may be anticipated that some one of the three pairs that contain X_3 will reduce the sum of squares of X_0 more strongly than other pairs that do not include X_3. This is so in table 3, but in some instances the relative importance of the several variables may shift as the analysis progresses.

The last column of table 3 indicates that the combination of mean grain size and moisture content shows the greatest reduction in the sum of squares of X_0, but this is not much greater than the reduction shown by moisture alone in table 2. The effect of including mean grain size with moisture results in a further reduction in the sum of squares of 4.21%. Inclusion of the phi standard deviation shows an increase of only 0.92%, and porosity adds a wholly negligible 0.02%. These are striking changes in terms of the first stage of analysis, where mean grain size, for example, effected a reduction of nearly 34% in the sum of squares of X_0.

THE SUM OF SQUARES CRITERION

As pointed out in the Appendix, the sum of squares of a dependent variable in any problem is a measure of the total variability that is to be "accounted for" by the independent variables involved. When a line or surface is fitted to the data, the fitted function reduces this sum of squares by a greater or lesser amount. This reduction is a measure of the mathematical relation between dependent and independent variables, and not necessarily a measure of the physical relation between them. However, if the problem is stated in terms of meaningful variables that are obviously or intuitively related to the physical problem, it is generally reasonable to assume that the independent variable which shows the strongest mathematical relation to the dependent variable also has the strongest physical relation to the phenomenon under study. There is no assurance, however, that an error of judgment cannot be made. Such errors arise from spurious correlations among the variables, or from unexamined

relations to more basic variables that are not explicitly part of the study.

When the independent variables are taken one at a time, their relative rank cannot in general be determined directly from the degree to which they reduce the sum of squares of the dependent variable. This arises from interrelations among the independent variables themselves, which are not brought out when they are considered individually. Some of the variables may be redundant in the sense that their apparent relation to the dependent variable is influenced in part by their own relation to other independent variables in the set. That such redundancies are present in the Wilmette example can be seen by adding the individual reductions in the sum of squares of X_0 in table 2. This sum is 125.15%, indicating that some variables, when taken one at a time, show stronger relations than they would show if taken in combination with other independent variables.

The second part of the analysis, as summarized in table 3, shows that when moisture is paired with the other variables, the reduction in the sum of squares due to the pair is considerably less than that due to the two variables taken singly. The decrease in the effect of mean grain size, for example, from nearly 34% to 4.21%, as mentioned, is an indication that mean grain size "repeats" information already supplied by the moisture content.

The strongest variable itself may be influenced by other variables, and if the criterion of the reduction in the sum of squares of X_0 is not physically sound, even the apparently strongest variable may be showing a spurious effect. When the grounds for accepting the strongest variable on a physical basis are sound, however, it is conventionally taken at face value, and the effects of other independent variables combined with it are expressed in terms of the added reduction contributed by the paired variable. Thus from table 3, the difference between the 74.00% reduction due to moisture plus mean grain size, and the 69.79% reduction due to moisture alone (table 2), is taken as the net contribution of mean grain size in the presence of the moisture effect.

INTERPRETATION OF THE WILMETTE RESULTS

It is believed that the sum of squares criterion is valid in the present example, except possibly in connection with interpretation of the packing effect. That is, the question of the reliability of the data, as well as the meaningfulness of the variables chosen, affects the results. Table 2 shows that porosity, X_4, reduces the sum of squares of X_0 by less than 1%, which is markedly lower than any of the others. This may mean that there is no relation between firmness and porosity, or that porosity is not a suitable measure of packing, or that the porosity measurements were so approximate that the "true" relation is hidden by large experimental errors. The writer inclines to the opinion that measurement error is a factor here, inasmuch as some loss of sample volume during collection of wet samples was noted. At the time it was thought that the loss was not significant, but it appears that the losses gave porosity values much too high for some of the wet samples.

A counteracting factor here arises from the fact that mean particle size is definitely smaller for the wet samples, on the average, than for the dry samples, and this would tend to increase the firmness, judging by the relation shown in the firmness-grain size diagram of figure 1. The last seven samples in table 1 average 0.25 mm mean diameter as against 0.47 mm for the preceding 18 samples of relatively dry sand. This suggests that mean grain size may be the main modifying factor on moisture content.

The second stage of analysis does nothing to improve the relative position of porosity among the independent variables, and the surprising part of this stage is that even mean grain size has only a small effect when the large contribution of moisture content is first taken into consideration. It may be inferred from the preceding paragraph, however, that the contribution of 4.21% to the total reduction in the sum of squares attributable to mean grain size is important enough to classify it as the second most important variable in the set. Inasmuch as the moisture content, mean grain size, and phi standard deviation are all measured with about the same level of accuracy, the analysis implies that mean grain size is

TABLE 4.—*Analysis of variance for evaluating importance of moisture content and mean grain size on beach firmness*

Source of variation	Sum of squares	Degrees of freedom	Mean square	*F*-ratio	Confidence level
Linear Relation of X_0 with X_3	90.0000	1	90.0000	50.82	99%+
Deviations from X_3 Linear	38.9583	22	1.7708		
Linear Relation of X_0 with X_1 after effects of X_3 are removed	5.4291	1	5.4291	3.41	90%+
Deviations from X_3, X_1 Linear	33.5292	21	1.5966		

more important than the degree of sand sorting, and that both are considerably weaker than the moisture effect. The position of sand packing seems indeterminate in this example.

The foregoing reasoning is based wholly on least squares analysis, which requires no assumptions about the distribution of the variables concerned, but does require a strictly subject-matter evaluation of the results. If the assumption can be made that the deviations from the linear regression functions are normally distributed, then, to an approximation at least, one may apply analysis of variance techniques to the analytical results to determine the likelihood that some of the regression lines or surfaces could arise purely by chance in samples from a homogeneous population. Studies of beach firmness measurements from closely-spaced samples indicate that this variable is distributed essentially normally, and hence the assumption of normally distributed deviations from the regression functions is not extreme.

Table 4 shows an analysis of variance of beach firmness in terms of moisture content and mean grain size. The reduction in the sum of squares due to moisture is taken as 69.79% of the total sum of squares, and that due to mean grain size in the presence of the moisture effect is taken as 4.21%. As the *F* ratio shows, the confidence level for moisture is 99%, and that for mean grain size is 90%. From an estimation rather than a hypothesis-testing viewpoint, it may be concluded for this example that both moisture and mean grain size exert a geologically important control on beach firmness.

Figure 2 is a block diagram illustrating the control of firmness by mean grain size and moisture content simultaneously. The surface was constructed by using the *a*, *b*, and *c* coefficients from Table 3 for X_1 and X_3 in the form of equation (2): $X_0' = 4.60 + 5.29\ X_1 - 0.20\ X_3$. Values of the linear surface were computed for the range 0 to 25% moisture, and 0.2 to 0.6 mm mean grain diameter, approximately the range of the experimental data. As the diagram shows, ball penetration descends from a high value for large dry grains to a small value for small wet grains. Inasmuch as firmness is greatest when penetration is least, the surface indicates that the greatest firmness is associated with small wet grains, and the least firmness with large dry grains. The surface also shows that small dry grains are slightly less firm than large wet grains.

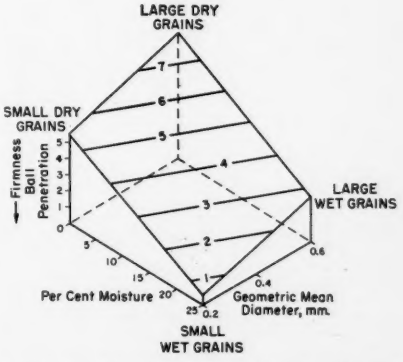

FIG. 2.—Linear component trend surface of ball penetration on moisture content and mean grain size of beach sand.

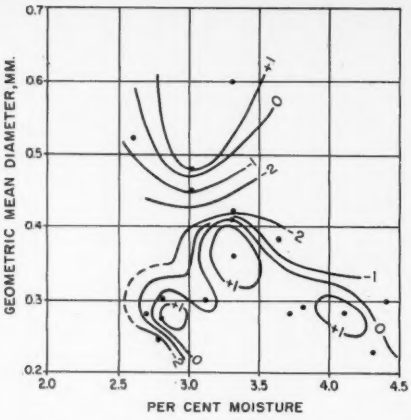

FIG. 3.—Deviations (residuals) of ball penetrability for a portion of the linear surface of figure 3.

The block diagram of figure 2 may be interpreted as the linear trend surface component (Krumbein, 1959) of ball penetration with respect to the independent variables mean grain size and moisture content. Although trend surface analysis is commonly applied to mapped sedimentary variables (Miller, 1956) where some dependent variable X_0 is examined as a function of its geographic co-ordinates (U, V), the same kind of analysis and interpretation can be applied to graphs as in figure 2, where X_1 and X_3 replace the variables U and V.

Departures of the observed data from the computed trend surfaces in map analysis may themselves be mapped to show the residuals on the trend (Krumbein, 1959) and similar graphs may be made with the data of this example. Figure 3 illustrates a portion of the residual (deviation) graph related to figure 2. The graph shows that for relatively dry sand the ball penetration is greater than would be expected (positive deviations on the linear surface) for coarser and finer sands having between 3% and 4% moisture. Intermediate diameters in this moisture range have negative residuals. This relation implies that a weak quadratic tendency may be present in the data for this part of the graph. Figure 3 thus shows in part the pattern of the residual variability in X_0 that is "unexplained" by the linear relation with mean grain size and moisture content.

COMPARISON OF THE WILMETTE DATA WITH OTHER SETS OF DATA ANALYZED BY THE SAME PROCEDURES

Table 5 summarizes the Wilmette example treated here plus four other early sets of data from Lake Michigan beaches in which measurements were made on the same group of five variables. All the data compare in quality with those from Wilmette.

TABLE 5.—*Comparison of several sets of beach data*

Beach area	Date	No. of samples	Method of measuring firmness	Single most important variable	Reduction in SS of X_0	Most important pair	Reduction in SS of X_0
Wilmette, Illinois 01 0075[2]	1949[1]	24	Ball penetration	Moisture	69.8%	Moisture. Grain size	74.0%
Evanston, Illinois 01 0030	1950	25	Cone penetration	Moisture	47.0%	Moisture, Porosity	61.7%
Wilmette, Illinois 01 0076	1949	20	Cone penetration	Moisture	84.1%	Moisture, Grain size	87.7%
Evanston, Illinois 01 0078	1950	20	Cone penetration	Moisture	46.7%	Moisture, Grain size	49.0%
Wilmette, Illinois 01 0077	1951	30	Cone penetration	Moisture	70.9%	Moisture, Porosity	77.8%

[1] Example treated in text.
[2] IBM 650 project number.

Moisture content ranks highest in all five studies and accounts for an average of 63.7% of the sum of squares of X_0. In three studies mean grain size ranks as the second most important variable, but adds an average of only 3.3% to the reduction in the sum of squares, whereas porosity adds an average of 10.8% to the reduction in the two studies where it ranks as second most important variable.

The results in table 5 suggest that moisture is the dominant variable in beach firmness, with mean grain size or porosity second. When the two dominant variables are used, the average sum of squares reduction in table 5 is 70%. When all four independent variables are included in subsequent stages of analysis, the two lesser variables together add less than 5% to the sum of squares reduction. Thus, in the first example the added effect of including both sorting and porosity reduces the total sum of squares by 76.6%, an increase of only 2.6% over moisture and grain size. That is, for the examples studied, the residual variability left after all four variables are included in the regression equation is still 25% or more.

Unexplained variability always raises questions, such as whether the measurements include large errors, whether the data are subject to very local fluctuations that tend to obscure underlying relations (Miller, 1956, p. 426), whether some other variables not included in the study—such as particle shape—may be exerting a strong effect, or whether the relations among some variables are non-linear.

This last point needs to be examined in detailed studies designed specifically for regression analysis. On some beaches the wet sand near the water line is definitely less firm than moist sand farther up on the foreshore. This implies that beach firmness shows a quadratic relation to moisture content of the general form:

$$X_0' = a + bX_3 + c(X_3)^2 \qquad (3)$$

For the second stage of analysis in such situations the paired independent variables require an extension of equation (2) to the following:

$$X_0' = a + bX_3 + c(X_3)^2 + dX \qquad (4)$$

where X_0' is the computed value of X_0 on the regression surface, and X_t is the particular independent variable paired with moisture. A quadratic relation between beach firmness and moisture is probably to be expected in the general case, if firmness is an expression of the strength of the sand, as mentioned in an earlier part of this paper.

CONCLUDING REMARKS

The plan of analysis presented in this paper is part of a general multiple regression technique that has applications in a variety of geological situations where empirical relations are sought between some dependent variable and a selected set of independent variables that are believed to control the phenomenon under study. The analytical results may be used in part to guide subsequent laboratory experimentation or to provide a basis for predicting values of the dependent variable associated with given values of the independent variables.

Regression analysis has a close parallel in correlation analysis. Both have been applied in geology by various workers, from linear correlation between pairs of variables (Chenoweth, 1952, furnishes an example) to more advanced models as used by Griffiths (1597) and co-workers. The present paper emphasizes the possibilities of using multiple regression as a sequential procedure with a formalized high speed computer program.

Although an effort was made to extract some generalizations about beach firmness from the examples, it is not intended that this paper be considered primarily as a formally organized study of that subject. Rather, these earlier sets of data make it evident that generalizations about beach firmness based on field studies need to be designed to take explicit account of the physical meaning of the variables included in the study, of the reliability of the measurements made, and of the statistical framework of sample and population in which such studies can be most effectively conducted.

The writer is indebted to his colleagues in his Department of Geology at Northwestern University, to the Graduate School for supporting research funds, and to a large number of graduate students who participated

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APPENDIX

INTRODUCTION

The importance of the sum of squares of the dependent variable as a criterion in "sorting out" a set of independent variables suggests that this concept be made explicit for problems of the sort covered here. The following section is similar to the development in standard statistics texts (Croxton and Cowden, 1955, p. 463, for example) but is given here for completeness.

THREE SUMS OF SQUARES

Figure 4 illustrates the meaning of the total sum of squares of a dependent variable, X_0. The data are synthetic to provide an easily-computed example. The horizontal line in the scatter diagram is $X_0=\bar{X}_0=11.0$, the arithmetic mean of the observed values of the dependent variable. The vertical lines connecting each point to this horizontal line represent the deviations of the observed points from their mean value, $X_0-\bar{X}_0$. If these lengths are squared and summed, the resulting number is the total sum of squares of X_0, defined as:

$$SS_{X_0}=\Sigma(X_0-\bar{X}_0)^2 \qquad (5)$$

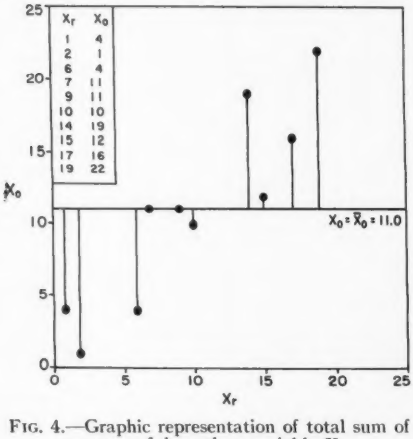

FIG. 4.—Graphic representation of total sum of squares of dependent variable X_0.

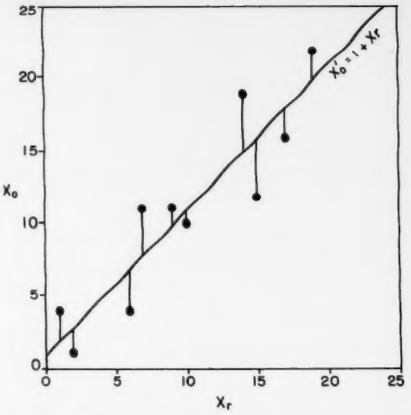

FIG. 5.—Graphic representation of sum of squares of deviations (residuals) from linear regression line fitted to points in figure 4.

where X_0 is a single observation and $\bar{X}_0$ is the mean. In figure 4 SS_{X_0} is the sum of $(4-11)^2+(1-11)^2+\cdots+(22-11)^2=410$. Thus, the "total variability" of X_0 is 410 units. The dimensions of the units depend on the variables used. If X_0 is a length, the sum of squares has the dimensions of a length squared.

Figure 5 shows the least squares straight line, $X_0'=a+bX_r$, fitted to the data of figure 4. Here X_0' is the computed value of X_0 along the straight line, a is the X_0-intercept, and b is the slope of the fitted line. In this example $a=b=1$, so that the relation is $X_0'=1+X_r$. The vertical lines connecting each observed point to the fitted line now represent the deviations of the observed points from their least squares computed values. When $X_r=1$, for example, $X_0'=2$, and the deviation of the first point from the line is $(4-2)=+2$. If all the deviations in the graph are squared and summed, the resulting number is the sum of squares of the deviations from the least squares line, defined as:

$$SS_D=\Sigma(X_0-X_0')^2 \qquad (6)$$

where X_0 is a single observation as before, and X_0' is the computed value of the straight line at the same point on the X_r axis. For figure 5, SS_D is the sum of $(4-2)^2+(1-3)^2+\cdots+(22-20)^2=68$. This number, 68, is the "residual variability" left in the observed data after the least squares straight line is fitted to the observations.

The method of least squares is so named be-

cause it selects values of the parameters a and b in $X_0' = a + bX_r$ such that the sum of squares of the deviations from the fitted line, measured in the same vertical sense as in figure 5, is smaller than it would be for any other straight line fitted to the same data. This is accomplished by equating SS_D as defined above to a function $G(a, b)$ that depends on the parameters a and b only. That is, $G(a, b) = \sum(X_0 - X_0')^2$. If the expression $a + bX_r$ is substituted for X_0' in this relation, the function $G(a, b) = \sum(X_0 - a - bX_r)^2$ can be differentiated with respect to a and b, and the derivatives set equal to zero in order to minimize the sum of squares. Thus,

$$\partial G/\partial a = 2\sum(X_0 - a - bX_r)(-1) = 0,$$

and

$$\partial G/\partial b = 2\sum(X_0 - a - bX_r)(-X_r) = 0.$$

By performing the indicated multiplication and summation, two *normal equations* are obtained;

$$\begin{aligned} aN + b\Sigma X_r &= \Sigma X_0 \\ a\Sigma X_r + b\Sigma X_r^2 &= \Sigma X_r X_0 \end{aligned} \qquad (7)$$

where N is the number of points in the graph, 10 here. Solution of these simultaneous equations for the data in figure 5 yields the values $a = 1$, $b = 1$, so that the least squares straight line in figure 5 has the form $X_0' = 1 + X_r$, as mentioned previously.

Although the method of least squares gives assurance that the residual variability represented by the sum of squares of the deviations will be a minimum, the "strength" of the relation between X_0 and X_r is commonly expressed in terms of the amount by which the fitted least squares function reduces the total sum of squares in X_0. That is, a third sum of squares is involved in the analysis, and it is associated with the fitted line or surface itself.

Figure 6 shows the same data as the two preceding figures, with the horizontal line $X_0 = \bar{X}_0$ taken from figure 4 and the least squares line taken from figure 5. If the vertical distances between these two lines, as indicated at the points of observation, are squared and summed, the resulting number is the sum of squares of the computed X_0' values, defined as:

$$SS_{X_0'} = \Sigma(X_0' - \bar{X}_0)^2 \qquad (8)$$

where X_0' is the computed value for each observed value of X_0, and $\bar{X}_0$ is the mean of the observed X_0 values. In least squares analysis the mean of the computed values, $\bar{X}_0'$, is equal to $\bar{X}_0$ inasmuch as the deviations from the least squares function have a zero sum within the limits of rounding. For the data in Figure 6, $SS_{X_0'}$ is the sum of $(2-11)^2 + (3-11)^2 + \cdots + (20-11)^2 = 342$. Thus, the least squares line has reduced the total sum of squares in X_0 by 342 units.

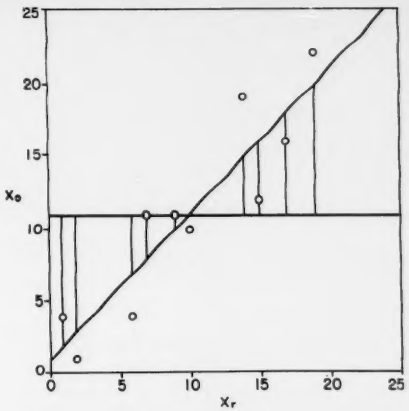

FIG. 6.—Graphic representation of sum of squares associated with linear regression line of figure 5. This sum of squares is a measure of the extent to which the independent variable X_r reduces the sum of squares of the dependent variable X_0.

The least squares analysis has in effect divided the total sum of squares of X_0 into two parts, one associated with the least squares line and the other with the deviations from the line. That is, $SS_{X_0} = SS_{X_0'} + SS_D$; in the present example, $410 = 342 + 68$. On a percentage basis, $SS_{X_0'}$ has reduced SS_{X_0} by $(100)(342/410) = 83.41\%$. In a statistical sense, the linear relation between X_0 and X_r "explains" 83.41% of the variability on X_0; the remaining 16.59% is "unexplained" by the linear relation.

MULTIPLE REGRESSION

The two stages of analysis defined by text equations (1) and (2) represent the extension of linear regression between two variables to multiple linear regression among three or more variables. The general form of the linear equation is:

$$X_0' = a + bX_r + cX_s + dX_t + \cdots \qquad (9)$$

where X_0' is the computed value of the dependent variable, and X_r, X_s, and X_t are the first three of an indefinite number of independent variables.

TABLE 6.—*Linear matrix and column vector for multiple regression analysis*[1]

$$\begin{bmatrix} N & SX_r & SX_s & SX_t & \cdots & SX_k \\ SX_r & SX_r^2 & SX_rX_s & SX_rX_t & \cdots & SX_rX_k \\ SX_s & SX_rX_s & SX_s^2 & SX_sX_t & \cdots & SX_sX_k \\ SX_t & SX_rX_t & SX_sX_t & SX_t^2 & \cdots & SX_tX_k \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ SX_k & SX_rX_k & SX_sX_k & SX_tX_k & \cdots & SX_k^2 \end{bmatrix} \begin{bmatrix} SX_0 \\ SX_rX_0 \\ SX_sX_0 \\ SX_tX_0 \\ \cdot \\ \cdot \\ SX_kX_0 \end{bmatrix}$$

[1] Summation designated as S instead of Σ.

The coefficient a is the X_0 intercept, and b, c, and d are the linear coefficients for the several variables, computed by least squares methods from the observations.

As expressed, equation (9) is linear in the coefficients and in the dependent and independent variables. However, as long as the coefficients remain linear, it is possible to introduce the independent variables with powers higher than 1. In text equation (3), where moisture entered as a quadratic term, the relation to equation (9) is that X_3 is used for X_r, and $(X_3)^2$ for X_s. In this manner the coefficients remain linear and the same general method of computation applies. When a second independent variable is paired linearly with moisture, the parallelism between equation (9) and text equation (4) is apparent.

For adapting equation (9) to the IBM 650 for the first stage of analysis, the normal equations in (7) are expressed in matrix algebra notation as follows:

$$\begin{bmatrix} N & \Sigma X_r \\ \Sigma X_r & \Sigma X_r^2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \Sigma X_0 \\ \Sigma X_r X_0 \end{bmatrix} \qquad (10)$$

The first expression on the left is the X_r-matrix, the second is the coefficient column vector, and the expression on the right is the column vector of the dependent variable. The machine inverts the matrix, multiplies it by the vector-X_0, and obtains the coefficient vector directly.

For additional independent variables the several parts of expression (10) are expanded by including additional coefficients, additional independent variables, and additional terms in the vector-X_0. Table 6 shows the form of the matrix and vector-X_0 for an indefinite number of independent variables. For the more comprehensive case, the machine sets up the complete matrix as in table 6, and then re-arranges the terms to obtain all possible variants of expression (10), using one independent variable at a time. This is the manner of obtaining the results in table 2.

For the second stage of analysis the machine arranges the independent variables into all possible pairs, using the appropriate cross-product terms (such as $\sum X_rX_s$) to obtain the results shown in table 3. Additional stages of analysis repeat the process with three, four, and more independent variables at a time.

In organizing the machine program, the first step is to use the observed data to compute the sums that enter the matrix and vector-X_0 of table 6. The machine then punches out the 2×2 matrices with their vector-X_0 cards, the 3×3 matrices with their vector-X_0 cards, and so on for larger matrices. These matrices are inverted by standard subroutines available in computing centers, and the inverted matrices are used with their vector-X_0 cards to compute the coefficients, also by subroutine. The output cards from the coefficient part of the program are then used with the original data cards to compute X_0' for each independent variable or combination. The computed values are subtracted from the observed X_0 values, and the differences, X_0-X_0' are obtained for graphs of the type shown in text figure 3. A final part of the program uses the output cards of the computed values and deviations to obtain the reduction in the sum of squares of X_0 associated with each regression relation, essentially as indicated in equations (5), (6), and (7).

MULTIPLE REGRESSION AND MULTIPLE CORRELATION

A parallel method to that described here is based on multiple correlation. In this second method all possible zero-order linear correlation coefficients for all the variables in the problem are computed. With one dependent variable and four independent variables, as in the text example, this gives rise to 4 correlation coefficients between the dependent variable and the independent variables taken one at a time, as well as 6 linear correlation coefficients between the independent variables themselves. As in the regression method, the independent variable that most greatly reduces the sum of squares of X_0 is picked

TABLE 7.—*Zero order correlation coefficients for Wilmette beach firmness example*

$r_{01} = 0.5824$	$r_{12} = 0.8848$	$r_{23} = -0.4388$	$r_{34} = -0.1151$
$r_{02} = 0.4526$	$r_{13} = -0.4819$	$r_{24} = -0.2576$	
$r_{03} = -0.8354$	$r_{14} = -0.2186$		
$r_{04} = 0.0982$			

as the strongest variable.

The strongest variable from the set of 4 independent variables is then "held constant" statistically by computing the first order partial correlation coefficients of the dependent variable and the remaining independent variables. This permits selection of the second strongest variable in the set, whereupon the second order partial correlation coefficients are computed, holding the first two statistically constant. This permits picking the third most important variable.

Table 7 lists the 10 zero order correlation coefficients, with subscripts indicating the variables involved. By squaring the correlation coefficients, the reduction in the sum of squares of X_0 by each independent variable is found directly. Thus, the largest r in the table is $r_{03} = -0.8354$. The square of this, expressed as a percentage, is 69.79%, as in table 2 of the text. The three first order partial correlation coefficients, holding X_3 constant, are $r_{01.3} = 0.3731$, $r_{02.3} = 0.1719$, and $r_{04.3} = 0.0036$. The square of the largest of these, $r_{01.3}$, expressed as a percentage, is 13.92%. That is, variable X_1 reduces the sum of squares of X_0 remaining after X_3 is removed, by 13.92%. This remainder is 100.00% − 69.79% = 30.21%. The partial correlation coefficient $r_{01.3}$ thus reduces the sum of squares of X_0 by 13.92% of 30.21%, which is 4.21%. The sum of 69.79% and 4.21% is 74.00%, the same result as obtained for variables X_1 and X_3 in table 3.

Details of the multiple correlation method are not given here. Croxton and Cowden (1955, chapter 21) give details, including a fully worked example. Both the multiple regression and multiple correlation methods are described in the same chapter, and the parallelism between them is clearly developed. The writer favors the regression method for several reasons, among which are the less stringent assumptions involved in regression, as well as the opportunity for each independent variable to enter each stage of the analysis, rather than having the strongest variable in any one stage held constant in all subsequent stages.

Mood (1950, p. 309–312) discusses the method of least squares, and makes some summary remarks on the assumptions that underlie regression and correlation analysis.

A third method of analysis involves use of deviations from the linear relation between the dependent variable and the strongest independent variable as a new dependent variable in the second stage of analysis, with repetition of this procedure for subsequent stages. That is, X_0 is used as dependent variable directly in the first stage, as in the other two methods, but for the second stage the dependent variable is defined as $(X_0 - X_0')$, the deviations from the strongest linear regression line.

The remarks in this last section of the Appendix are included to emphasize the point that several approaches to the problem of seeking for empirical relations among a given set of variables are available for application to geological problems. All are based on least squares methods, and the choice among them may be governed by the objectives of the analysis, by the assumptions that may safely be made about the data, and by subsequent statistical tests that the worker may wish to apply to testing the validity of inferences drawn from the analysis.

REFERENCES

CHENOWETH, P. A., 1952, Statistical methods applied to Trentonian stratigraphy in New York: Geol. Soc. America, Bull., v. 63, p. 521–560.

CROXTON, F. E., AND COWDEN, D. J., 1955, Applied general statistics, 2nd ed., New York, Prentice-Hall, Inc., p. 843.

GRIFFITHS, J. C., 1957, Petrographical investigation of the Salt Wash sediments: U. S. Atomic Energy Commission, RME-3151, p. 38.

KRUMBEIN, W. C., 1959, Trend surface analysis of contour-type maps with irregular control-point spacing: Jour. Geophys. Research, v. 64, p. 823–834.

MILLER, R. L., 1956, Trend surfaces: their application to analysis and description of environments of sedimentation: Jour. Geology, v. 64, p. 425–446.

MOOD, A. M., 1950, Introduction to the theory of statistics: New York, McGraw-Hill, p. 433.

TAYLOR, D. W., 1948, Fundamentals of soil mechanics, New York, John Wiley and Sons, p. 700.

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FIGS. 1–2, DECEMBER, 1959

MINERAL COMPOSITIONS CALCULATED FROM CHEMICAL ANALYSES OF SEDIMENTARY ROCKS[1]

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ABSTRACT

A method is described for routine calculation of mineralogical compositions from chemical analyses of sedimentary rocks. Although designed for the particular mineral suites found in the Florena Shale (a mid-continent Permian argillaceous unit containing calcite, dolomite, chert, and clay as major constituents), it can be adapted with slight modification for use with a wide variety of sedimentary rock types. After restating the bulk analysis in terms of molecular ratios, TiO_2, Na_2O, P_2O_5, SO_3, and S are disposed of as rutile, albite, apatite, gypsum, and pyrite. Next, all of the CaO and CO_2 and as much MgO as is required, are used to form calcite and dolomite. The balance of the MgO and all of the K_2O are then used to form illite and either sericite or chlorite, depending on the relative amounts of MgO and K_2O. Residual Fe_2O_3 and Al_2O_3 are computed as montmorillonite and residual SiO_2 is regarded as chert. Results of computation compare well with X-ray and insoluble residue data and the method is judged to provide an estimate of the proportions of clay, dolomite, calcite, and chert accurate to within 5 per cent.

INTRODUCTION

For several years, Imbrie (1955) has been engaged in a detailed study of stratigraphic facies exhibited in the Florena Shale (Permian of Nebraska, Kansas, and Oklahoma). Statistical techniques of facies analysis and synthesis are employed throughout, and it is therefore necessary to obtain quantitative lithologic data on a large number of samples. The petrographic nature of the Florena Shale makes this objective difficult to attain: Ninety per cent of most samples are composed of silt- and clay-size grains of clay, calcite, dolomite, and chert. Particularly vexing is the difficulty of distinguishing fine-grained chert from clay. Acid leaching may alter both the amount and nature of the residual clay, and any attempt to separate clay from chert mechanically leaves an unknown amount of fine-grained silica with the clay. The fine grain-size together with the friable nature of the rock make quantitative study of thin sections impractical. Differential thermal analyses made by Norton (1956) give useful qualitative results but considerable difficulty is encountered in dealing quantitatively with a four-component system.

The opportunity to solve these problems by chemical recalculation was provided by a large number of analyses made under the direction of Mr. Russell T. Runnels of the Division of Geochemistry, State Geological Survey of Kansas. It soon became evident as calculation progressed, that the compositions of many Florena minerals are so complex and variable that the labor of computation would be unduly prolonged unless some routine system were devised. The computation form presented in this paper is the result of our efforts to speed up the calculations. After a little experience with its use, this form makes it possible to transform an oxide analysis into a mineral analysis in about a half-hour's time if a desk calculator is available. Using this form we were able to calculate over 100 complete mineral analyses covering a lithologic range from nearly pure limestone, to nearly pure dolomite, to a clay shale, and a wide variety of intermediate types (see fig. 1). Considerable interest in this calculation form has been expressed by other workers and one objective of this paper is to make it generally available.[2]

Students of igneous rocks are familiar with the system of re-calculating chemical analyses used by Cross, Iddings, Pirsson, and Washington (1903). Although similar kinds of computations are described for sedimentary rocks by Krumbein and Pettijohn

[1] Manuscript received June 29, 1959.

[2] Printed copies of the form may be obtained at a cost of 5 cents each from the authors.

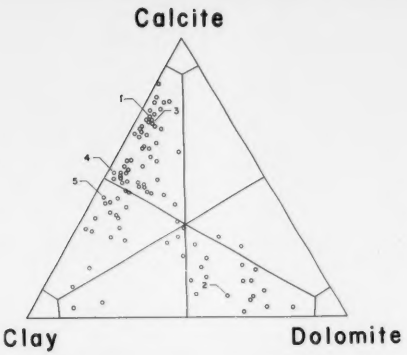

FIG. 1.—Diagram showing the compositions of 93 samples of Florena Shale as computed from chemical analyses. The field is subdivided into arbitrary portions with lines corresponding to 50 and 10 percent compositions. 1=sample 2–2b, 2=sample 10–4a, 3=sample 13–1c, 4=sample 14–1a, and 5=sample 15–2a.

(1938, p. 490), their use in this field has been limited. This can probably be attributed in part to the high cost of chemical analyses and in part to the inconvenience of calculations. By providing a routine method of computation we hope to encourage more studies of this kind.

The computation form was originally presented (Imbrie and Poldervaart, 1957) in a slightly different form, with sphene instead of rutile, and sepiolite ($2MgO \cdot 3SiO_2 \cdot 4H_2O$) instead of chlorite. Changes incorporated in this paper are the result of criticisms by Brough and Robertson (1958), R. T. Runnels (personal communication, 1958) and others.

DESCRIPTION OF CALCULATION FORM

Selection of mineral suite.—Mineral species identified from the Florena Shale by various techniques are listed in table 1. From this tabulation it is possible to draw up the folllowing preliminary list of minerals for computation:

Albite	Chert	Illite
Apatite	Calcite	Montmorillonite
Hematite	Dolomite	Chlorite
Pyrite	Ferrodolomite	Sericite

Illite and montmorillonite must be treated as separate minerals, although this does injustice to the actual mineralogical mode of occurrence as determined by X-ray methods. Two minerals had to be assumed in order to reflect the stated chemical analyses completely: gypsum, to use up SO_3, and rutile for TiO_2. In no case did these hypothetical minerals exceed a trace amount. Chemical compositions of all minerals used in computation are give in table 2.

TABLE 1.—*Minerals identified in the Florena Shale*

Technique	Minerals identified
Binocular microscope	Apatite Calcite Chert Hematite Pyrite
Potassium ferricyanide stain	Ankerite
Petrographic microscope	Albite Calcite Chert Dolomite
D.T.A.	Calcite Dolomite Illite Montmorillonite Quartz
X-ray diffraction	Fine-grained mica Illite-montmorillonite interlayer mixture Chlorite Kaolinite

TABLE 2.—*Chemical compositions used in calculating mineral components of the Florena Shale*

Mineral observed	*Ideal composition*
Pyrite	FeS_2
Apatite	$3CaO \cdot P_2O_5$
Albite	$Na_2O \cdot Al_2O_3 \cdot 6SiO_2$
Calcite	$CaO \cdot CO_2$
Dolomite	$CaO \cdot MgO \cdot 2CO_2$
Ferrodolomite	$CaO \cdot FeO \cdot 2CO_2$
Illite	$2K_2O \cdot 3MgO \cdot (Al_2O_3, Fe_2O_3)_8 \cdot 24SiO_2 \cdot 12H_2O$
Sericite	$K_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$
Hematite	Fe_2O_3
Montmorillonite	$(Al_2O_3, Fe_2O_3)_2 \cdot 8SiO_2 \cdot 2H_2O$
Chlorite	$4MgO \cdot 2Al_2O_3 \cdot 2SiO_2 \cdot 4H_2O$
Chert	SiO_2
Mineral assumed	
Gypsum	$CaO \cdot SO_3 \cdot 2H_2O$
Rutile	TiO_2

It is apparent that the calculation system embodied in the form below will not always be applicable. The known mineralogy of each sample must be considered and treated appropriately.

Explanation of the form.—Step I: The first step in using the form (fig. 2) is to enter in the appropriate boxes on the left-hand side weight percentages of the various oxides of the chemical analysis. Each of these is then converted into the molecular proportion by dividing the oxide weight by the corresponding molecular weight, and the result entered in the appropriate box. It is usually de-

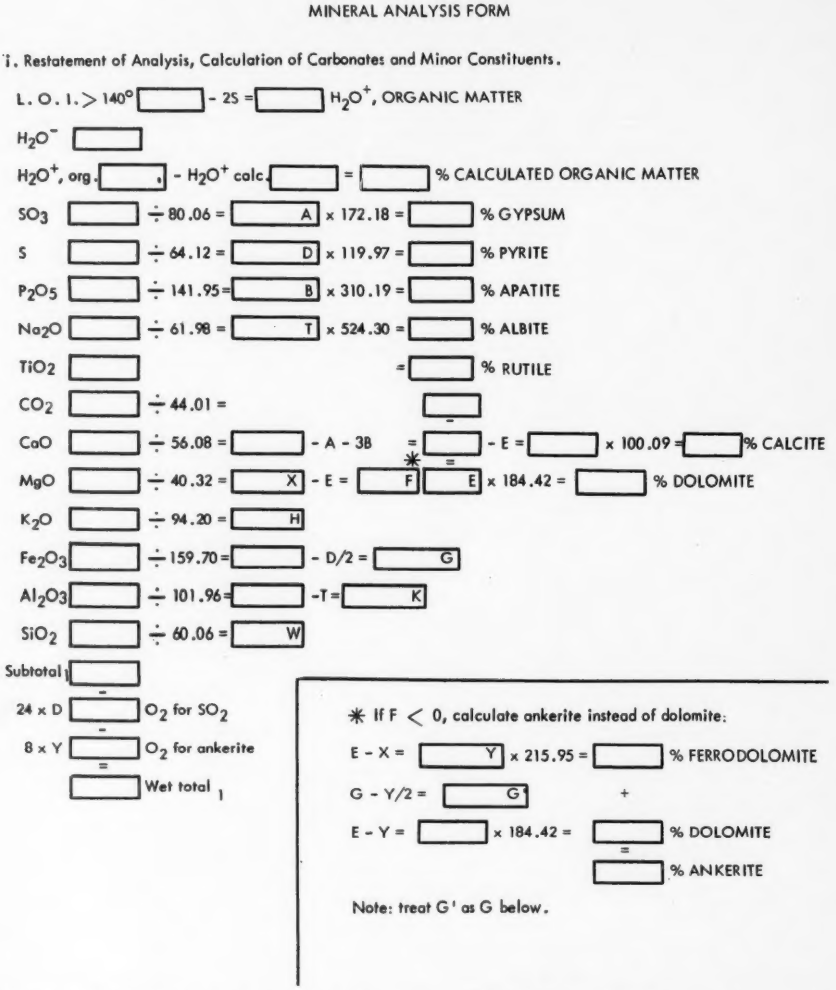
MINERAL ANALYSIS FORM
I. Restatement of Analysis, Calculation of Carbonates and Minor Constituents.
L. O. I. > 140° - 2S = H2O+, ORGANIC MATTER
H2O-
H2O+, org. - H2O+ calc. = % CALCULATED ORGANIC MATTER
SO3 ÷ 80.06 = A x 172.18 = % GYPSUM
S ÷ 64.12 = D x 119.97 = % PYRITE
P2O5 ÷ 141.95 = B x 310.19 = % APATITE
Na2O ÷ 61.98 = T x 524.30 = % ALBITE
TiO2 = % RUTILE
CO2 ÷ 44.01 =
CaO ÷ 56.08 = - A - 3B = - E = x 100.09 = % CALCITE
MgO ÷ 40.32 = X - E = F E x 184.42 = % DOLOMITE
K2O ÷ 94.20 = H
Fe2O3 ÷ 159.70 = - D/2 = G
Al2O3 ÷ 101.96 = -T = K
SiO2 ÷ 60.06 = W
Subtotal 1
24 x D O2 for SO2
8 x Y O2 for ankerite
Wet total 1
* If F < 0, calculate ankerite instead of dolomite:
E - X = Y x 215.95 = % FERRODOLOMITE
G - Y/2 = G'
E - Y = x 184.42 = % DOLOMITE
% ANKERITE
Note: treat G' as G below.

FIG. 2.—Calculation form for computing mineral compositions from chemical analyses of sedimentary rocks. For explanation see text. (Continued in figs. 2b and 2c.)

ii. Calculation of Clay Minerals and Hematite.

(A) If 3H/2F ≧ 1, calculate MgO as illite, balance of K_2O as sericite.

MgO [F] ÷ 3 = [L] x either 2840.46 or J = [ ] % ILLITE

K_2O [H] - 2L = [M] x 796.48 = [ ] % SERICITE

(1) If 8L - K > 0, compute illite and hematite.

8L - K = [Q] ÷ 8L = [ ] x 461.92 = [ ] + 2782.72 = [J]

G - Q = [ ] x 159.70 = [ ] % HEMATITE

(2) If 8L - K < 0, regard illite as 2840.46 and compute montmorillonite.

Al_2O_3 [K] - 3M - 7L = [ ] 115.48 V/U = [ ]

Fe_2O_3 [G] - 1L = [V] 720.44

[U] ÷ 2 = [Z] x [ ] = [ ] % MONT.

(B) If 3H/2F < 1, and G - Δ > 0, calculate K_2O as illite, balance of MgO as chlorite.

K_2O [H] ÷ 2 = [N] x either 2840.46 or I = [ ] % ILLITE

MgO [F] ÷ 4 = [ ] - .75 N = [P] x 557.40 = [ ] % CHLORITE

(1) If 8N - K > 0, compute illite and hematite.

8N - K = [Δ] ÷ 8N = [ ] x 461.92 = [ ] + 2782.72 = [I]

G - Δ = [ ] x 159.70 = [ ] % HEMATITE

(2) If 8N - K < 0, regard illite as 2840.46 and compute montmorillonite.

Al_2O_3 [K] - 7N -2P = [ ] 115.48 V/U = [ ]

Fe_2O_3 [G] - 1N = [V] 720.44

[U] ÷ 2 = [R] x [ ] = [ ] % MONT.

(C) If 3H/2F < 1 and G - Δ < 0, compute sericite, Fe-sericite, montmorillonite, and chlorite.

Fe_2O_3 [G] x 854.22 = [ ] % Fe-SERICITE

K_2O [H] - G = [α] x 796.48 = [ ] % SERICITE

MgO [F] ÷ 4 = [β] x 557.40 = [ ] % CHLORITE

Al_2O_3 [K] -2G -3α -2P = [ ] ÷ 2 = [θ] x 720.44 = [ ] % MONTMORILLONITE

FIG. 2b.—*See* caption of fig. 2a.

sirable to carry five decimal places in calculation. For simplicity, this number of places is assumed throughout and decimal points and zeros are eliminated. An entry of 99, for example, represents a molecular proportion of 0.00099. Each blank box on the calculation form having some special significance is designated by a symbol, usually a capital letter, so that this quantity may be conveniently and unambiguously referred to

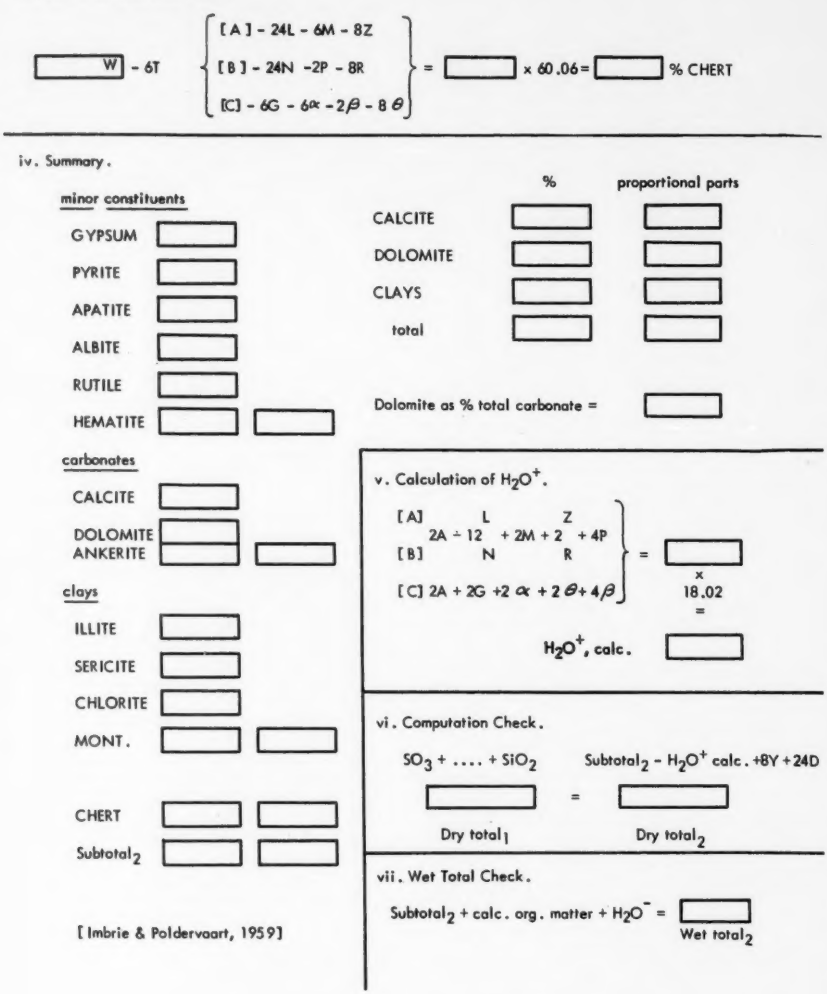

FIG. 2c.—*See* caption of fig. 2a.

again. Thus A stands for the molecular proportion of SO_3, T the molecular proportion of Na_2O, and so on. In some cases a symbol stands for a quantity needed for more complex types of calculation.

Step II: Calculate minor constituents by multiplying molecular proportions of the key oxides (A, D, B, and T) by the appropriate molecular weight.

Step III: Calculate carbonates as follows: From the molecular proportion of CO_2 subtract the proportion of CaO remaining after

allowing for CaO used in gypsum and apatite (total CaO$-\underline{A}-3\underline{B}$). The balance ($\underline{E}$) represents the amount of dolomite necessary to use up all of the CO_2. By subtracting $\underline{E}$ from the available CaO, the molecular proportion of calcite is determined. When total MgO and CaO are insufficient to use up CO_2 ($\underline{F}<0$), ferrodolomite is calculated as indicated.

Step IV: The quantities $\underline{F}$, $\underline{H}$, $\underline{G}$, $\underline{K}$, and $\underline{W}$ are computed as indicated. These represent the proportions of MgO, K_2O, Fe_2O_3, Al_2O_3, and SiO_2 remaining at this stage of the calculation, and available for clay, hematite, and chert. Statement of the molecular proportion of Fe_2O_3 ($\underline{G}$) involves a correction for the use of ferrous iron in pyrite. Chemical analyses available to the writers did not separate ferrous from ferric iron, hence all of the iron is stated as Fe_2O_3.

Step V; In calculating clays, two first-order alternatives are possible, depending on the relative proportions of K_2O and MgO. If the ratio $3\,\underline{H}/2\underline{F}$ equals or exceeds 1 (alternative iiA), all of the MgO is computed as illite, and the balance of the K_2O not used as illite is computed as sericite. If $3\,\underline{H}/2\,\underline{F}$ is less than 1, two second-order alternatives (iiB and iiC) are possible, depending on the relative amount of Fe_2O_3 and K_2O. If ($Fe_2O_3-4K_2O+Al_2O_3$) is greater than zero ($\underline{G}-\Delta>0$), the K_2O is calculated as illite, and the remaining MgO as chlorite (alternative iiB). If ($G-\Delta<0$), the remaining oxides with the exception of silica are computed as sericite, iron-rich sericite, montmorillonite, and chlorite (alternative iiC). Two third-order alternatives are possible (iiB_1 and iiB_2), depending on the relative amounts of K_2O and Al_2O_3 ($8\underline{N}-\underline{K}$). If K_2O is in excess of the designated proportion, illite and hematite are calculated; if K_2O is less than the designated proportion, illite and montmorillonite are calculated. In calculating weight percentages of illite and montmorillonite which contain varying amounts of Fe_2O_3 and Al_2O_3, provision has been made for determining the appropriate molecular weights.

Step VI: SiO_2 unused up to this point is now totaled and calculated as chert.

Step VII: Blank spaces are provided on the form for entering totals of minor constituents, carbonates, clays, and chert. For purposes of the Florena study it was desirable to represent each sample on a triangular diagram having as end-members calcite, dolomite (including ankerite), and total clay. Blank spaces to facilitate this calculation are also provided.

Step VIII: Compute the total bound water (H_2O+) as indicated in item v.

Step IX: Two different checks are built into the form. The first (item vi) checks the accuracy of the arithmetical work by ignoring the figure for loss on ignition representing SO_2, H_2O^-, H_2O^+, and organic matter. A dry total calculated by adding the stated weight percentages of oxides from SO_3 through SiO_2 is compared with a dry total calculated by summing the calculated weight percentages of minerals (subtotal$_2$), from which the calculated bound water is subtracted. It is also necessary to take into account a discrepancy introduced by the fact that iron used in the calculation of ankerite and pyrite is actually ferrous iron. This is done by adding the factors $8\underline{Y}$ and $24\underline{D}$.

Step X: Finally, the original stated analysis including loss on ignition may be compared with the computed total including bound water. This is done (items i and vii) by computing two "wet" totals. Wet total$_1$ is derived as follows: From the figure given for loss on ignition $>140°$C.($H_2O^+ + SO_2$ +organic matter) subtract the weight lost by evolution of SO_2. This gives a figure for the total of H_2O^+ and organic matter, which when added to the determined H_2O^- and the remaining oxides gives subtotal$_1$. This must now be corrected for oxygen used in forming ankerite and SO_2. Wet total$_1$ is now compared with wet total$_2$ determined by adding subtotal$_2$ (the sum of computed minerals), the figure for computed organic matter, and the observed H_2O^-. The "wet total check" is sensitive not only to inaccuracies of laboratory procedure in determining the various losses on ignition but also to incorrect assumptions as to the state of hydration of the clay minerals.

Table 3 gives chemical analyses of five samples of Florena Shale. Mineralogical compositions computed for these are entered in table 4. Proportions of calcite, dolomite,

TABLE 3.—*Chemical analyses of the Florena Shale*[a]

Sample	CaO	MgO	CO_2	SiO_2	Al_2O_3	TiO_2	Fe_2O_3[b]	K_2O	Na_2O	SO_3	S	P_2O_5	L.O.I.	Total
2-2b	37.27	1.82	29.74	19.62	5.01	0.56	1.94	0.91	.15	.10	—	.08	2.79	99.99
10-4a	19.50	11.10	27.09	26.23	7.69	0.27	3.19	1.60	.25	.05	—	.09	3.12	100.18
13-1c	37.95	2.05	31.11	17.68	5.35	0.30	1.59	0.95	.19	—	—	.05	2.47	99.69
14-1a	20.61	2.07	16.51	37.87	10.43	0.69	2.88	1.78	.47	—	—	.03	6.56	99.90
15-2a	18.41	1.52	14.70	41.91	11.10	0.81	2.99	1.85	.52	.07	.45	.01	5.16	99.05

[a] Russell T. Runnels, State Geological Survey of Kansas, analyst.
[b] Total iron expressed as Fe_2O_3.

TABLE 4.—*Calculated analyses of the Florena Shale*

Sample	Gypsum	Pyrite	Apatite	Albite	Rutile	Hematite	Calcite	Dolomite	Illite	Mont.[a]	Sericite	Chlorite	Total Clay	Chert
2-2b	.21	—	.17	1.27	.56	—	64.03	3.32	13.72	5.42	—	1.76	20.90	8.07
10-4a	.11	—	.20	2.11	.27	—	7.28	50.05	3.66	14.71	11.47	—	28.84	8.64
13-1c	—	—	.11	1.60	.30	—	64.50	5.76	14.32	6.34	—	0.62	21.28	5.14
14-1a	—	—	.07	3.97	.69	—	35.89	1.52	26.84	11.22	—	2.05	40.11	13.92
15-2a	.15	.84	.02	4.39	.81	—	32.07	1.26	27.89	13.43	—	0.20	41.52	15.94

[a] Montmorillonite.

and clay as computed are indicated graphically on figure 1.

ACCURACY OF THE METHOD

For purposes of the Florena study, only a modest measure of accuracy is required, on the order of ± 5 percent for the major constituents (chert, calcite, dolomite, and total clay). From several lines of evidence we are confident that this order of accuracy is achieved. This opinion is based partly on theoretical and partly on empirical grounds.

Essentially all of the CaO must be considered as calcite and dolomite so that the amounts of CO_2 and CaO uniquely determine the proportions of the (ideal) carbonate minerals. MgO not used in dolomite, together with all of the K_2O, Al_2O_3, and Fe_2O_3 must next be used to form various clay minerals. In spite of the fact that the chemical formulae for clays are complex and variable, a few attempts to employ these oxides in different ways will show that the figure for total clay cannot, in any major way, be altered.

Two laboratory tests provide a check on the accuracy of the computed compositions. The first is a carefully run set of six hydrochloric acid insoluble residues. Results of these are given in table 5, where the observed insoluble residue is compared with the total clay and chert computed from the chemical analyses. Considering that the two sets of analyses were performed on separate "cuts" of the same sample, the degree of correspondence is remarkable. The average discrepancy (0.7 percent) is clearly not significant. From this we conclude that the calculation method gives a reliable figure for total clay plus chert. The second check is provided by X-ray diffraction analyses of the same samples, carried out by Professor Edward Jonas, of the University of Texas. In table 6 his results are compared with our calculated compositions. Agreement between the two sets of figures for quartz,[3] al-

TABLE 5.—*Comparison of observed and computed insoluble residue percentages in six samples of Florena Shale*

Sample no.	Computed clay and chert	Observed insoluble residue	Difference
10-1	36.5	34.9	+1.6
10-2b	53.4	51.6	+1.8
10-2d	56.7	56.9	−0.2
10-4a	38.0	35.2	+2.8
10-4c	44.2	46.9	−2.7
10-4e	43.4	46.0	−2.6

Average difference: +0.7

[3] Dr. Jonas determined the quartz by an addition technique in which known amounts of quartz were added to each sample, and the increase in intensity of one of the quartz diffraction lines was recorded. An internal standard of 20 percent apatite was used to account for instrumental variation.

TABLE 6.—*Analyses for clays and quartz by X-ray and calculation techniques*

Sample	X-ray analyses[a]								Calculated analyses				
	Percent total clay				Percent Mixture[b]			Percent quartz	Percent quartz	Percent total clay			
	Kaolinite	Chlorite	Mica	Mixture	CaMo.[c]	Illite	NaMo.[d]			Sericite	Illite	Mo.[e]	Chlorite
2-2b	0	20	80	tr	?	?	?	7.5	8.1	0	66	26	8
10-4a	0	20	80	tr	?	?	?	4.0	8.6	38	12	49	0
13-1c	0	tr	10	90	30	60	10	3.0	5.1	0	67	30	3
14-1a	0	tr	10	90	30	50	20	11.5	13.9	0	67	28	5
15-2a	10	tr	10	80	40	60	0	13.5	15.9	0	67	32	1

[a] Edward Jonas, University of Texas, analyst. Clay figures accurate to ±5%; quartz, ±1%.
[b] Interlayer mixture of illite and montmorillonite.
[c] Calcium montmorillonite.
[d] Sodium montmorillonite.
[e] Montmorillonite.

though imperfect, is remarkably good. The largest error (sample 10-4a) is about 5 percent; in the remaining four samples it is about 2 percent. In all cases the calculated analyses are in excess of those determined by X-ray, which probably reflects the fact that none of the calcium, sodium, or titanium has been included in the calculated clay. Combining insoluble residue and X-ray data, we may conclude that compositions computed from chemical analyses by this method give figures for total clay, free silica, and total carbonates with an accuracy of about 5 percent. Since it is known that the only carbonate minerals present in these samples are calcite and dolomite, it follows that errors in the calculation of the proportions of these minerals are less than 5 percent.

Examination of table 6 shows that there is little agreement between the two methods as regards proportions of the various clay minerals. This is hardly surprising in view of the many possible ionic substitutions in the clays, e.g. Al for Si in the tetrahedral sheet, or Mg, Fe, and Al for each other in the octahedral sheet. Even when the principal clay minerals in a sample have been identified, the accuracy of computation of their relative quantities from the bulk chemical composition depends largely on the number and kind of mineral phases involved, and the variability of their composition due to isomorphous replacement.

REFERENCES

BROUGH, J., AND ROBERTSON, R. H. S., 1958, A chlorite convention for the appraisal of Scottish fireclays: Clay Minerals Bulletin, v. 3, p. 221–231.

CROSS, W., IDDINGS, J. P., PIRSSON, L. V., AND WASHINGTON, H. S., 1903, Quantitative classification of igneous rocks: Univ. Chicago Press, Chicago, 286 p.

IMBRIE, JOHN, 1955, Quantitative lithofacies and biofacies study of Florena shale (Permian) of Kansas: Am. Assoc. Petroleum Geologists, Bull., v. 39, p. 649–670.

KRUMBEIN, W. C., AND PETTIJOHN, F. J., 1959, Manual of sedimentary petrography. Appleton, Century, Crofts, Inc., New York 549 p.

NORTON, M. F., 1956, The mineralogy of the Florena shale. Unpublished Masters thesis, Columbia University, New York, N.Y.

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FIGS. 1–3, DECEMBER, 1959

ANALYSIS OF FACTORS AFFECTING QUANTITATIVE ESTIMATES OF ORGANISM ABUNDANCE[1]

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ABSTRACT

Examination of the physical relationship between weight and volume sediment samples, and comparison of estimates of organism abundance obtained from equal volume and equal weight samples of recent sediment show that kinds of minerals forming the sediment have little effect on abundance distribution patterns determined by counting the number of specimens in samples of a given weight or volume, and that variation in sediment porosity probably is the major factor responsible for differences between organism counts based on equal weight samples and those based on equal volume samples.

Consideration of the diagenetic processes of compaction and cementation that affect organism abundance shows that for sediments, which have not been materially changed by processes such as intrastratal solution, replacement, and recrystallization, abundance counts from recent and ancient sediments are more comparable if clays and shales are reported on the basis of equal weight samples, and unlithified and lithified sands are reported on the basis of equal volume samples.

INTRODUCTION

Analyses of the distribution of the remains of dead organisms in recent sediments is strongly influenced by the method used to establish and report abundance counts. Comparisons of abundance counts from recent and ancient strata are affected by the composition of the sediment, its history, and the type of sample upon which counts are based.

The abundance of dead forms in recent sediments may be used to interpret past environments (Kornicker, 1957), to estimate relative sedimentation rates (Walton, 1955) and may serve as a basis for making comparisons with the abundance distribution of fossil organisms. Horizontal or vertical variation in fossil abundance may be useful in stratigraphic correlations (Ellison, 1951), and can be utilized in reconstructing conditions attending the depositional environment (Imbrie, 1955).

Counts of abundance of the remains of dead organisms from recent sediments usually have been expressed in terms of equal weight, equal dry volume, and equal wet volume samples (Schott, 1935; Parker, 1948; Said, 1950; Walton, 1955). Most abundance counts from ancient strata have been made on a weight basis (Ellison, 1951; Imbrie, 1955; Echols and Gouty, 1956).

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This paper presents an attempt to explore the general relations between weight and volume sediment samples in order to determine the advantages and disadvantages of each type sample.

COMPARISONS OF ABUNDANCE COUNTS BASED ON VOLUME AND WEIGHT SAMPLES OF RECENT SEDIMENTS

The absolute density of minerals forming the major part of marine sediments does no vary greatly, and therefore mineral density has little effect on abundance distribution patterns determined by counting the number of specimens in samples of a given weight or volume. For example, if a sediment sample composed entirely of aragonite grains (specific gravity 2.94 gm/cc) contains the same number of organisms as a sample composed entirely of montmorillonite (specific gravity 2.4 gm/cc) and both samples have the same porosity and volume, the number of organisms recorded in the two samples would differ by only about 14 percent, providing the counts were made from equal weight samples (See table 1 for additional examples). Mineral density would have no effect on abundance estimates made from equal volume samples.

Porosity (volume percentage of pore space) of recent marine sediments varies considerably. Porosity is dependent on pack-

TABLE 1.—*Comparison of the number of specimens from equal volume and equal weight hypothetical sediment samples composed of different minerals*

Composition of sediment	Mineral density grams per cc	Number of specimens per cc[a]	Number of specimens per gram[b]	Difference in number of specimens
Aragonite	2.94	100	34	66
Calcite	2.72	100	37	63
Dolomite	2.87	100	35	65
Montmorillonite	2.4	100	42	58
Illite	2.6	100	38	62
Average clay	2.7	100	37	63
Quartz	2.66	100	38	62

[a] One hundred specimens per cc is hypothetical and chosen only for the purpose of the table.
[b] Number of specimens per one gram was obtained by dividing the number of specimens per cc (100) by density of mineral composing the sediment. Calculation based on hypothetical porosity of 0 percent.

ing, shape and uniformity of grains, and grain size. The porosity of coarse sand is usually 35 to 40 percent, whereas freshly deposited clay may have a porosity of 50 percent or higher (Pettijohn, 1949, p. 69, 277). Mississippi delta mud, according to Meinzer (1923, p. 8), has a porosity ranging from 80 to 90 percent. Shaw (1915, p. 1415) found the porosities of mud deposits on the sea coast to range from 40 to 90 percent. Terzaghi and Peck (1948, p. 29) reported a soft slightly organic clay having a porosity of 66 percent and a soft very organic clay with a porosity of 75 percent. Walton (1955, p. 992) collected a sediment from station B-45 in Todos Santos Bay having only 4.28 grams total dry weight in a volume of 10 cubic centimeters of wet sediment. If a density of 2.7 grams per cubic centimeter is assumed for the solids in this sample, the porosity would be roughly 84 percent.

The relationship between the number of organisms per dry weight of sample and per volume of sample is shown by the following equation:

$$(1) \qquad X_{dw} = \frac{100\, X_v}{\rho(100-P)}$$

where X_{dw} is the number of organisms per gram of dry sediment, X_v is the number of organisms per cubic centimeter of sediment, P is porosity of sediment, ρ is the grain density in grams per cubic centimeter. The sample may be in dry or wet state when volume is determined, but dry porosity must be used with dry volume and wet porosity with wet volume. By using the above equation a graph was constructed from which the number of organisms per gram of dry weight may be determined directly from the number of organisms per cubic centimeter of sample, providing the grain density of the sample is 2.7 grams per cubic centimeter and the porosity of the sample is known (fig. 1). The number of individuals per sample are identical when based on either weight or volume only when the porosity of the sediment is 63 percent. If the porosity of a sediment is above 63 percent, counts based on weight are higher than counts based on

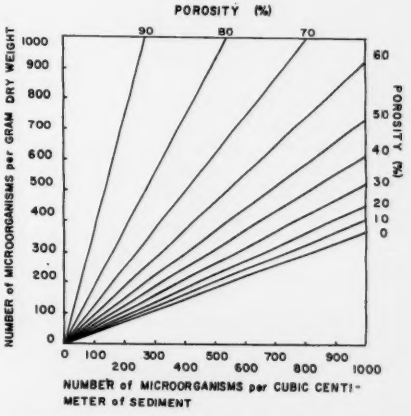

FIG. 1.—Theoretical relationships between the number of organisms per cubic centimeter and gram dry weight of sediment. Wet porosity is used with samples based on wet volume. Dry porosity is used with samples based on dry volume. A density of 2.7 gm/cc has been assumed for sediment grains in the construction of this graph.

TABLE 2.—*Comparison of abundance counts based on volume and dry weight hypothetical sediment samples having different porosities*[a]

Porosity of sediment %	Number of organisms per 1 cc[b]	Number of organisms per 1 gram dry weight[c]
30	500	265
50	500	370
84	500	1150

[a] Absolute density of 2.7 grams per cc is assumed for mineral composing sediment.
[b] Number microfauna per cc is hypothetical and assumed expressly for the purpose of this table.
[c] Values obtained from figure 1.

volume. If porosity is below 63 percent, counts based on weight are lower than counts based on volume.

Variation in sediment porosity probably is the major factor responsible for differences between organism abundance counts based on equal weight samples and those based on equal volume samples. Hypothetical microorganism counts based on volume and dry weight sediment samples having different porosities are compared in table 2.

COMPARISON OF ABUNDANCE COUNTS BASED ON WET AND DRY RECENT SEDIMENT SAMPLES OF EQUAL VOLUME

The volume occupied by a given weight of a sediment is affected by the manner of packing of the grains. Clays, or clayey sediments shrink upon drying and, therefore, the volume of a given weight of dry clay is less than the volume when the clay was in a wet state. However, if the dried clay is pulverized, its volume is likely to increase. Athy (1930) and Frazer (1935) have demonstrated that the volume of some sands deposited in water can be reduced 11 to 13 percent by compaction and jarring.

The relationship between the number of organisms in wet and dry samples of equal volume is shown by the following equation:

$$X_d = \frac{X_w(100-P_d)}{(100-P_v)} \qquad (2)$$

where X_w is the number of organisms per cubic centimeter of wet sediment, X_d is the number of organisms per cubic centimeter of dry sediment, P_d is the porosity of the dry sediment, and P_v is the porosity of the wet sediment.

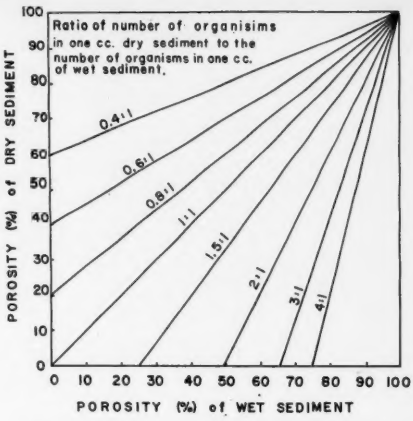
Ratio of number of organisms in one cc. dry sediment to the number of organisms in one cc. of wet sediment.
0.4:1
0.6:1
0.8:1
1:1
1.5:1
2:1
3:1
4:1
POROSITY (%) of DRY SEDIMENT
POROSITY (%) of WET SEDIMENT
0 10 20 30 40 50 60 70 80 90 100

FIG. 2.—Theoretical relationship between the number of organisms in a unit volume of wet and dry sediment.

This equation has been plotted graphically in figure 2. From this graph the number of organisms per cubic centimeter of wet sediment may be obtained from the number of organisms in one cubic centimeter of dry sediment, providing the wet and dry porosities are known. Organism abundance from hypothetical wet and dry samples of equal volume are compared in table 3.

TABLE 3.—*Comparison of organism counts based on wet volume and dry volume hypothetical sediment samples having various wet and dry porosities*

Wet porosity (%)	Dry porosity (%)	Number organisms per 1 cc wet volume[a]	Number organisms per 1 cc dry volume[b]
30	30	500	500
30	15	500	605
30	10	500	650
50	50	500	500
50	25	500	750
50	10	500	900
84	42	500	1800
84	10	500	2800

[a] Five hundred specimens per one cc is hypothetical and chosen only for the purpose of the table.
[b] From figure 2.

DIAGENETIC PROCESSES AND THEIR EFFECT ON ABUNDANCE COUNTS

Diagenetic processes that lead to lithification are compaction, cementation, intrastratal solution, authigenesis and metasomatism (Pettijohn, 1948, p. 477).

Compaction.—As soon as sediment is buried it is subjected to compaction and attendant water loss. According to Athy (1930, p. 8) clay probably assumes an average porosity of about 50 percent after the accumulation of an overburden a few tens of feet in thickness although the surface clays may vary from 50 to 90 percent in porosity.

Compaction of sand is relatively small (see Pettijohn, 1948, p. 69; Athy, 1930, p. 8; Trask, 1931, p. 274; Fraser, 1935, p. 942). Calcareous or sandy shale compaction is comparable with pure shales (Athy, 1930, p. 9). Weller (1959) has pointed out that the uncrushed condition of empty shells in limestones indicates that very little compaction occurs in limestones. Trask (1931, p. 274) has shown experimentally that colloids are compacted more than clays, clays more than silts and silts more than sands.

Compaction will have little effect on abundance counts reported from equal weight samples. Compacted sediment will contain more specimens than the same volume of uncompacted material. An approximation to the number of specimens per sample present on ancient depositional surfaces may be realized from determinations of the abundance of fossil organisms in compacted sediments providing initial and present porosities are known (equation 1).

$$x=\frac{y(100-P)}{(100-P_c)} \tag{3}$$

where y is the number of specimens in unit volume of sample of compacted sediment, P_c is the porosity of compacted sediment, P is the original porosity of sediment, and x is the number of specimens in the same unit volume of sediment when in previous position on the sea floor.

Example: If

$y=500$ Foraminifera per 10 cc of compacted sediment

$P_c=10\%$

$P=50\%$ (estimated)

then

$$x=\frac{500(100-50)}{(100-10)}$$

$=278$ Foraminifera per 10 cc of sediment before compaction

In general, the porosity of clay and shale is a function of depth of burial. Athy (1930, p. 13) has related porosity and depth of burial in equation (4).

$$P=p(e^{-bx}) \tag{4}$$[2]

where P is porosity, p is the average porosity of surface clays, b is a constant, and x is the depth of burial.

As the decrease in porosity is principally the result of a decrease in volume, it is possible to predict the theoretical increase in number of specimens per unit volume due to compaction at depth (fig. 3). According to these data, the number of specimens of microfauna per unit volume of clay at the surface would increase by 40% at a depth of 1000 feet and 80% at a depth of 6000 feet as a result of compaction.

Porosity has been found to decrease when a sediment is deformed. Rubey (1930, p. 36) expressed the relationship of porosity and deformation in equation (5).

$$P_u=100-\cos d(100-P_p) \tag{5}$$

where P_u is porosity of untilted rock, d is present angle of dip, and P_p is present porosity.

The number of specimens per unit volume of sediment would theoretically be increased about 8 percent in rock dipping 4–5 degrees, and as much as 20 percent with steeper dips.

Cementation.—Although compaction of sands is negligible, cementation, caused by the addition of a cementing material in pore spaces, is commonplace. As an illustration the average sand has a porosity of 35 to 40 percent, whereas the average sandstone has a porosity of 15 to 20 percent (Pettijohn, 1948, p. 69). In contrast relatively little cementation occurs in shales (Athy, 1930, p. 9). According to Weller (1959) the consolidation of most limestones is probably the result of cementation. Pore filling by a secondary mineral that causes a decrease in rock porosity increases the weight per unit volume. Therefore the number of specimens will be lower in a unit

[2] For recent discussion of this equation, the reader is referred to Weller (1959).

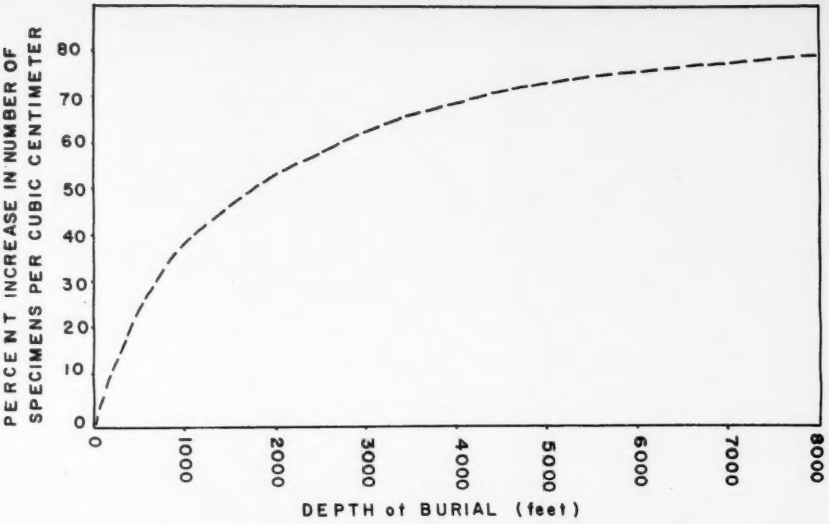

FIG. 3.—Theoretical increase in the number of organisms per unit volume of clay caused by compaction at depth. The curve is based on porosity changes at depth given by Athy (1930).

weight of cemented sediment than in a unit weight of uncemented sediment.

Intrastratal Solution.—Intrastratal solution will generally decrease the number of microorganisms per sample regardless of the sample base because the fragile carbonate shells of Foraminifera and Ostracoda are destroyed quite easily. Siliceous Foraminifera, conodonts, and fish remains may be more resistant. In the Florena Shale of Kansas, for example, only siliceous Foraminifera are found in the upper part of many vertical sections, although both calcareous and siliceous forms occur in the lower part. This distribution may be partially the result of intrastratal solution in the upper part of the sections. Occasionally, siliceous minerals are dissolved and replaced by calcite, but this is considered exceptional (Pettijohn, 1948, p. 492).

Authigenesis.—The formation of new minerals in place is usually termed authigenesis (Pettijohn, 1948, p. 478). Aragonite deposited on the sea floor usually converts to calcite in a relatively short time with a decrease in density from 2.94 to 2.72 grams per cc. Montmorillonite is converted to illite with an increase in density from 2.4 to 2.6 grams per cc. Replacement and recrystallization may or may not destroy all or part of the organisms. However, assuming that the organisms are not destroyed, the number of specimens per sample, on a weight basis, will be affected only slightly by change in density of the enclosing sediment (*see* table 1).

Where deformation, recrystallization, replacement, or intrastratal solution have removed some of the organisms, reliable reconstruction of the original number of individuals is not possible unless special conditions of preservation are known to have occurred such as preservation within chert nodules.

CONCLUSIONS

1. A study of the quantitative distribution of dead organisms in recent sediment is strongly influenced by the method used to establish and report abundance counts, unless the porosity of the sediments in the sampling area is fairly uniform or unless the areal variation in abundance of individuals is sufficiently large to minimize porosity variation.

2. Abundance counts from shale will be more comparable with counts from recent clays if both are reported from equal weight samples. Abundance counts from cemented sand will be more comparable with counts from recent sands if both are reported from equal volume samples. The tendency for limestones to become consolidated by cementation rather than by compaction suggests that abundance counts from limestones will be more comparable with counts from recent carbonate sands if both are reported from equal volume samples.

3. The difference between the volumes occupied by sediment in a wet or dry state may be inconsequential for sands but considerable for clays and other fine grained sediment. The impracticality of basing abundance counts on wet samples of ancient strata makes the wet volume sample, which is currently being used extensively as the basis for abundance counts of dead microorganisms in recent sediments, least useful for comparing recent and fossil abundances.

ACKNOWLEDGMENTS

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REFERENCES

ATHY, L. F., 1930, Density, porosity, and compaction of sedimentary rocks: Am. Assoc. Petroleum Geologists, Bull., v. 14, p. 1–35.

ECHOLS, D. J. AND GOUTY, J. G., 1956, Fern Glen (Mississippian) Ostracoda: Jour. Paleontology, v. 30, p. 1315–1323.

ELLISON, S. P., 1951, Microfossils as environment indicators in marine shales: Jour. Sedimentary Petrology, v. 21, p. 214–225.

FRASER, H. J., 1935, Experimental study of the porosity and permeability of clastic sediments: Jour. Geology, v. 43, p. 910–1010.

IMBRIE, J., 1955, Quantitative lithofacies and biofacies study of Florena Shale (Permian) of Kansas: Am. Assoc. Petroleum Geologists Bull., v. 39, p. 649–670.

KORNICKER, L. S., 1957, Ecology and taxonomy of recent marine ostracodes in the vicinity of Bimini, Bahamas. Columbia University thesis.

MEINZER, O. E., 1923, The occurrence of ground water in the United States: U. S. Geol. Survey Water-Supply Paper 489, 110 p.

PARKER, F. L., 1948, Foraminifera on the Continental Shelf from the Gulf of Maine to Maryland: Mus. Comp. Zoology Bull., v. 100, No. 2, p. 214–241.

PETTIJOHN, F. J., 1949, Sedimentary rocks. Harper and Brothers, New York, 526 p.

RUBEY, W. W., 1930, Lithologic studies of fine-grained Upper Cretaceous sedimentary rocks of the Black Hills region: U. S. Geol. Survey Prof. Paper 165-A, 54 p.

SAID, RUSHDI, 1950, The distribution of Foraminifera in the northern Red Sea: Contr. Cushman Found. Foram. Res. v. 1, No. 3, p. 9–29.

SCHOTT, W., 1935, Die Foraminiferen in dem Aequatorialen Teil des Atlantischen Ozeans: Deutsche Atlantische Exped. Meteor 1925–1927, Bd. 3, Teil 3, p. 43–134.

SHAW, E. W., 1915, The role and fate of connate water in oil and gas sands: Am. Inst. Min. Met. Eng. Bull., v. 103, p. 1451.

TERZAGHI, K., and PECK, R. B., 1948, Soil mechanics in engineering practice. John Wiley and Sons, Inc., New York, 566 p.

TRASK, P. D., 1931, Compaction of sediments: Am. Assoc. Petroleum Geologists Bull., v. 15, p. 271–276.

WALTON, W. R., 1955, Ecology of living benthonic Foraminifera, Todos Santos Bay, Baja California: Jour. Paleontology, v. 29, p. 952–1018.

WELLER, J. M., 1959, Compaction of sediments: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 273–310.

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FIGS. 1–2, DECEMBER, 1959

ZEOLITES IN SEDIMENTARY ROCKS[1]

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ABSTRACT

Zeolite minerals, especially analcime and clinoptilolite, are known to occur widely in sedimentary rocks both as nearly monomineralic beds and as accessory minerals. Because of the extremely fine grain size of the zeolite rocks, identifications are made most readily with X-ray diffraction techniques. A survey of the known occurrences of sedimentary zeolites shows that most, if not all, of these minerals were formed during diagenesis by the alteration of volcanic material. Rhyolite glass from vitric ash falls may be altered during diagenesis to clay minerals, zeolites, or authigenic feldspars; the mineralogy of the diagenetic products is a promising indicator of post-depositional chemical environments.

INTRODUCTION

The increasingly frequent recognition of zeolite minerals as diagenetic products formed in sedimentary environments and the lack of discussion of these materials in most textbooks on sedimentary petrology warrants a summary of the occurrences of diagenetic zeolites and a discussion of their mode of origin. Under some conditions vitric ash alters to nearly monomineralic zeolite rocks in a manner analogous to the way in which bentonites are formed. A new rock name is needed for rocks containing more than 50 percent of one or more zeolites. Although in sedimentary sequences these rocks are often referred to informally as zeolite beds, the term *zeolitite* is preferable as a formal rock name. Sedimentary rocks containing zeolite minerals as cement or as accessory authigenic crystals are also well known.

Laboratory work on the synthesis of zeolites suggests that information about the chemical and physical conditions during diagenesis can be derived from the zeolite mineralogy but at present neither the synthesis data nor the study of the natural occurrences is sufficiently complete to outline specific conditions for each zeolite. Nevertheless all of the laboratory data indicate that zeolites form only in alkaline environments (Noll, 1936; Eskola et al., 1937; Stringham, 1952; Morey and Ingerson, 1937).

MINERALOGY

Most of the sedimentary zeolites occur as extremely fine-grained aggregates which are usually impossible to identify in hand specimen and they are frequently too fine-grained for accurate optical measurements. As a result, the zeolites in these rocks are most readily indentified by X-ray techniques. The powder pattern of each structural type is quite distinctive although compositional varieties having the same structural framework give similar X-ray patterns. In figure 1 diffractometer traces are shown of the zeolites which have been reported most often from sedimentary rocks.

General mineralogical descriptions of the zeolites are available in reference works on mineralogy, but it should be pointed out that in this and other studies the refractive indices of several zeolite species occasionally have been found to lie well outside of the range reported in reference lists.

The rocks composed of zeolite are usually characterized by low specific gravity, extremely fine grain size, and moderate hardness (although the rock can be quite tough if it contains fibrous zeolites and it can be very hard when silicified). The outlines of altered glass shards can be distinguished occasionally both in thin sections and on weathered surfaces. Diatomite, fine-grained vitric ash, and rocks composed of authigenic

[1] This paper is a portion of a thesis submitted to the faculty of Princeton University in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The author wishes to acknowledge the guidance of Professor F. B. Van Houten during the progress of this work. Manuscript received May 6, 1959.

feldspar can have an appearance in hand specimen that is almost identical to that of the zeolite rocks.

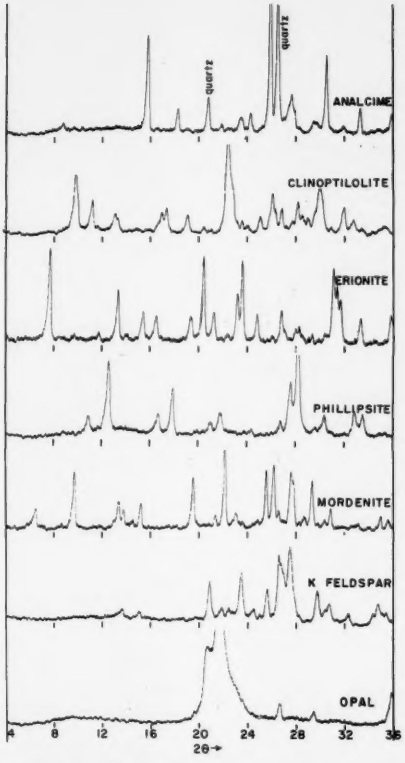

FIG. 1.—X-ray diffractometer traces using nickel filtered copper radiation of the common sedimentary zeolite species. All of the traces are of bulk samples of unusually pure monomineralic sedimentary rocks, except for mordenite which is from a mineral specimen. The analcime was collected by T. W. Donnelly, the remainder of the material was collected by the author.

Analcime—Green River Formation, Sweetwater County, Wyoming
Clinoptilolite—Fish Creek Mountains, Nevada
Erionite—Red Canyon, Shoshone Range, Nevada
Phillipsite—Pine Valley, Nevada
Mordenite—Challis, Idaho (hydrothermal vein)
Monoclinic Potash Feldspar—Tepee Trail Fm., Sand Draw, Wyoming
Opal—Opalized wood, Jersey Valley, Nevada

The available reports of the occurrence of zeolites in sedimentary rocks indicate that analcime and clinoptilolite are by far the most common; phillipsite and erionite are known in a few localities. Although several other zeolite species have been reported, in every case there is some question either about whether the material is of diagenetic origin or about the identification of the mineral.

Clinoptilolite, the high silica variety of heulandite, gives an X-ray powder pattern that is almost identical to ordinary heulandite. The two types can be distinguished by chemical analyses, optical properties (Hey and Bannister, 1934), or thermal stability (Mumpton, 1958). Those studies that have distinguished between the two minerals indicate that most, and possibly all, of the occurrences in sedimentary rocks are clinoptilolite.

An X-ray comparison of analcime, noncubic analcime, and wairakite was made by Coombs (1955), but at present only cubic analcime has been reported as a diagenetic product. Phillipsite and erionite are readily identified from their X-ray powder patterns. Chemical analyses of phillipsite show a larger variation than is found in other zeolites, and a thorough study might suggest a subdivision of the species.

It should be pointed out that in spite of the number of reports of the occurrence of mordenite in sedimentary rocks (Wanless, 1922; Bushinsky, 1950; Rengarten, 1945; Vasil'ev, Koblin, and Krasnova, 1956; Vasil'ev, 1954; and Ermolova, 1955), not one of the studies has reported X-ray results. During this study an X-ray examination of the "mordenite" reported by Wanless (1922) showed the material to be a mixture of erionite and clinoptilolite. Hayashi and Sudo (1957) have identified mordenite by X-ray methods in altered pyroclastic rocks in Japan, however in their opinion the Japanese deposits were formed by hydrothermal alteration.

PUBLISHED DESCRIPTIONS

Table 1 summarizes occurrences of zeolites in sedimentary sequences, most of which bear no special evidence of alteration by processes other than diagenetic changes at low temperature. The table includes de-

TABLE 1.—*Summary of occurrences of zeolites in sedimentary rocks*

Minerals Reported	Locality	Association	Age	References
Analcime	Popo Agie Fm., west central Wyoming	With quartz, carbonates, and iron oxides, at top of redbed sequence	Triassic	Keller (1952)
Analcime	Chinle Fm., eastern Utah	Yellowish to brown silty clay and limestone Fe oxides, calcite, dolomite, quartz	Triassic	Keller (1953)
Analcime	Tepee Trail Fm., Lysite Mtn., Wyoming	Low grade oil shale, coal, with gray, black, or green beds of analcime	Eocene	Tourtelot (1946)
Analcime	Green River Fm., Utah and Wyoming	With volcanic minerals and opal in altered ash in oil shale containing calcite, dolomite and pyrite, and clay	Eocene	Bradley (1929) Dane (1954)
Analcime	Lockatong Fm., New Jersey	Black lacustrine argillite with illite, carbonates, and quartz	Triassic	Van Houten and Olsen (1957)
Analcime	Mendoza, Argentina	Dark colored shales and tuffs, analcime "sandstones" derived by alteration of tuff	Triassic?	Baldwin (1944)
Analcime	Tongue River Member of Fort Union Fm. near Ludlow, South Dakota	Analcime crystals in a thin uraniferous lignite in gray shale	Paleocene	Rozendal (1956)
Analcime	Western Georgia, U.S.S.R.	Coal bearing strata containing a shale and sandstone horizon with analcime as cement or as spherules	Jurassic	Dzotsenidze, Skhirtladze, Chechelashvili (1956)
Analcime	Kirov region, U.S.S.R.	Marine sediments with decomposed volcanic material, with gypsum and carbonates	Kazanian Zechstein	Rengarten (1940)
Analcime	Chkalova district, along Ural River, U.S.S.R.	Microscopic crystals in sandstones, limestones, and marls	Permian	Boldyreva (1953)
Analcime	Wikieup, Arizona	Brown clay, limy sand, green arkosic sand—playa deposit	late Cenozoic	Ross (1928, 1941)
Analcime Clinoptilolite	Hector, California	Tuffaceous lacustrine sediments with travertine, chalcedony nodules, brown mudstone, calcite, gypsum, hectorite and Al bentonite	Pliocene?	Ames, Sand, Goldich (1958)
Clinoptilolite	Salt Lake Group, southern Idaho	Fine-grained gray to greenish-gray massive rock	Pliocene	Originally identified by L. B. Sand, confirmed by this study
Clinoptilolite	Santa Cruz Co., California	In friable marine arkose containing some volcanic glass fragments	Miocene	Gilbert and McAndrews (1948)
Clinoptilolite	Dome, Arizona	Bentonite with some fresh glass shards	—	Bramlette and Posnjak (1933)
Clinoptilolite	Monterey Group, California	Marine tuffaceous beds partially altered to clay and zeolite; opal and diatomites are common	Miocene	Bramlette and Posnjak (1933)
Clinoptilolite	Pierre shale, Pedro, Wyoming	In bentonite with some fresh glass remaining	Cretaceous	Bramlette and Posnjak (1933)
Clinoptilolite	Elko oil shale, Elko, Nevada	Beds of white zeolite in a sequence of dark brown to black oil shale; montmorillonite is present both in the oil shale and in the zeolite rocks	Oligocene	This report
Clinoptilolite	Kuttung Glacial Beds, New South Wales	Orange to red clinoptilolite altered from acidic glass shards in laminated sand and silt size rocks	Pennsylvanian	Coombs (1958)
Clinoptilolite	Techachapi, California	In bentonite associated with tuff and tuffaceous shale, in part opalized	"Late Tertiary"	Kerr and Cameron (1936)
Clinoptilolite	Fish Creek Mtns., Nevada	Thick pyroclastic bed, with pumice lumps and matrix converted to clinoptilolite	Mid-Cenozoic?	This report
Phillipsite Erionite Clinoptilolite	"Upper Buff" facies: Pine Valley, Shoshone Range, Reese Valley and Jersey Valley; central Nevada	In buff colored, tuffaceous lacustrine sedimentary rocks	Pliocene–Early Pleistocene	This report and Regnier (personal communication)
Erionite Clinoptilolite	Reese Valley, Shoshone Range Jersey Valley; central Nevada	In beds altered from volcanic ash associated with montmorillonitic mudstone and unaltered vitric tuff in lacustrine sediments	Early Pliocene	This report

TABLE 1.—(*Continued*)

Minerals Reported	Locality	Association	Age	References
Clinoptilolite	Jersey Valley and Pine Valley; central Nevada	Altered from volcanic ash in lacustrine sediments composed dominantly of montmorillonite and volcanic detritus	Late Miocene	This report and Regnier (personal communication)
Clinoptilolite Erionite	Tepee Trail Fm., Beaver Divide, Wyoming	With montmorillonite, opal and authigenic feldspar in volcanic-rich lacustrine sedimentary rocks	Eocene	Van Houten (1954 and personal communication)
Clinoptilolite Erionite	White River Fm., South Dakota	(Originally reported as mordenite) In cavities in sedimentary rocks containing abundant volcanic ash	Oligocene	Wanless (1922, p. 198), this report
Heulandite or Clinoptilolite	Ventura Quadrangle, California	In bentonite associated with marine shale and volcanic ash	Miocene	Kerr (1931)
Clinoptilolite or Heulandite	Jackson Fm., Karnes Co., Texas	Zeolitically altered tuffaceous sandstone	Eocene	Weeks, Levin, and Bowen (1958)
Heulandite or Clinoptilolite	Blackleaf sandy member of Colorado shale, northwestern Montana	Nonmarine bentonitic mudstone, clayey sandstone, tuff and bentonite; with red heulandite crystals, "Red speck zone"	Cretaceous	Cobban (1955, p. 110)
Heulandite?	Aurora, Utah	In bentonite associated with rhyolite ash, tuffaceous sandstone, agglomeratic tuff, zeolite postulated from recalculation of chemical analysis	—	Crawford and Cowles (1932)
Phillipsite Analcime	Pacific and Atlantic bottom sediments	Associated with volcanic materials in pelagic red clays in areas of extremely slow sedimentation	Recent	Murray and Renard (1891), Arrhenius and Goldberg (1955)
Analcime Natrolite	Tepee Creek Fm., Wichita Mtns., southwest Oklahoma	With calcite, dolomite, opal, Fe and Ti oxides, plagioclase, and pebbles of anorthosite and granite	Permian or Precambrian?	Merritt (1958, p. 56–58), Merritt and Ham (1941), Chase (1954), Mayes (1947)
Analcime Mordenite	Western Transcaucasia, U.S.S.R.	Widespread occurrences of authigenic zeolites in sandstones and siltstones	Oligocene Miocene	Ermolova (1955)
Analcime Mordenite	Lower Volga Basin and Western Kazakhstan, U.S.S.R.	Marine sand clays, with calcite, dolomite, chlorite, gypsum, glauconite, and phosphorite	Mesozoic Cenozoic	Vasil'ev (1954)
Mordenite	Southeast Russia	Widely distributed in marine sedimentary rocks with opal, quartz, chalcedony, and glauconite	Cretaceous Paleocene	Bushinsky (1950)
Mordenite	Eastern slope of the Ural Mountains, U.S.S.R.	Interstitial crystals in fine-grained quartz sandstones; crystallographic description similar to clinoptilolite	Cretaceous Paleocene	Rengarten (1945)
Mordenite	Penza oil prospect (Western Ukraine)	Marl, siltstone, gray limestone, glauconite, opal, marine sediments	Jurassic Cretaceous Paleocene	Vasil'ev, Koblin, Krasnova (1957)
Analcime Heulandite Laumontite	Southland, New Zealand	Tuffs and greywackes, in part altered by hydrothermal metamorphism	Triassic	Coombs (1950, 1952, 1954)
Analcime Laumontite	Northern Caucasus, U.S.S.R.	As cement in dolomitic ferruginous oolites and in sandstones	Jurassic	Rengarten (1950)
Analcime Laumontite	Tuva, Southern Siberia, U.S.S.R.	Phosphatic sandstones with analcime, laumontite, calcite, and collophane as cement; epidesmine also reported	Lower Carboniferous	Bur'yanova (1954, 1956)
Laumontite (Leonhardite)	Tejon Field near Bakersfield, California	Cement in a feldspathic sandstone from a well core taken at approximately 11,000 feet	Miocene	Kaley and Hanson (1955)
Laumontite	Anchor Bay, Mendocino County, California	Cement in sandstone	Cretaceous?	Gilbert (1951)
Laumontite	Wolf Creek, Montana	"resembles a compact although somewhat friable sandy clay of a dirty grayish pink color." Several veins in a distance of 5 meters, individual veins reaching a thickness of 0.6 meter	—	Shannon (1921)

scriptions published since 1900 of occurrences which were, in the original author's opinion, diagenetic or syngenetic in origin.

The author wishes to thank F. B. Van Houten, Jerome Regnier, and F. A. Mumpton for references to articles which made the list (table 1) more complete. Unfortunately some of the Russian articles have been examined only by way of abstracts available in Mineralogical Abstracts and Chemical Abstracts; in these cases the reference is followed by the Chemical Abstracts volume and column number. Those studies reporting high-silica heulandite are listed as clinoptilolite; those not distinguishing between the two species are listed as heulandite or clinoptilolite. Although variations in composition and optical properties coupled with extremely small grain sizes contribute to occasional errors in identification of zeolites, no attempt could be made at evaluating the accuracy of some of the identifications.

The most frequent association is the occurrence of zeolites with volcanic material, especially with vitric rhyolite ash. Opal is often present, probably as silica released when a zeolite is formed that has a lower silica content than the original glass. Authigenic feldspars are occasionally reported; the most common variety in these associations is monoclinic potash feldspar. A discussion of authigenic feldspars is given by Baskin (1956)

ORIGIN OF THE ZEOLITES

The mode of origin of the zeolites can be inferred partly from the occurrences and partly from the results of laboratory experiment. The occurrence of authigenic phillipsite and possibly analcime (Murray and Renard, 1891, analcime is listed on page 121, and Arrhenius and Goldberg, 1955) in association with volcanic material in the deep sea sediments demonstrates rather clearly than zeolites can form below room temperature. Every discussion of the phillipsite, erionite, clinoptilolite, and analcime in the late Cenozoic lake sediments in the western United States has classified the minerals as products of low-temperature reactions between the sediment (usually containing glass shards) and the lake water of restricted basins. Among older sedimentary rocks, however, the possibility arises that heated ground water or low temperature regional metamorphism might have had a part in producing the zeolites. Of the zeolites commonly found in sedimentary rocks, only laumontite has never been reported from a rock that has not been subjected to moderately deep burial or high temperatures. Fyfe, Turner, and Verhoogen (1958) have proposed a low-rank metamorphic facies with laumontite as a characteristic mineral, which they refer to as the "zeolite facies." Since a number of zeolite minerals are common even in the sedimentary rocks that are farthest removed from any question of metamorphism, it might be preferable to refer to the metamorphic facies as the "laumontite facies."

There is some evidence which suggests that there are zeolite associations which characterize certain sedimentary environments. The Late Miocene and Pliocene sections in the Great Basin have a history of nearly continuous sedimentation in an increasingly arid climate (Axelrod, 1950, p. 242–243). In the particularly long lacustrine section in Jersey Valley, Nevada, the basal portion contains only clinoptilolite but in younger parts of the section first erionite and later phillipsite appear either as relatively pure beds or as mixtures with clinoptilolite. Evidence from relic textures and from accessory minerals indicates that all of the zeolites are alteration products of vitric rhyolite ash. It is probable that during the Pliocene the increasingly saline and alkaline lake water was more capable of removing silica and adding alkalis to produce zeolites having compositions increasingly different from the composition of the parent material (fig. 2). Supporting evidence that the composition of the lake water can influence the zeolite mineralogy comes from Bradley's observation (1929, p. 4–5) that in the Green River Formation alteration of volcanic material to analcime occurred before the sediment was compacted.

LABORATORY EXPERIMENTS

Syntheses of zeolites have been reported in a number of hydrothermal experiments, but the stability fields of the individual zeolite minerals are not clearly defined. In an investigation of the Na_2O, Al_2O_3, SiO_2, H_2O system at 250° C and above, Sand, Roy, and Osborn (1957) observed that analcime forms

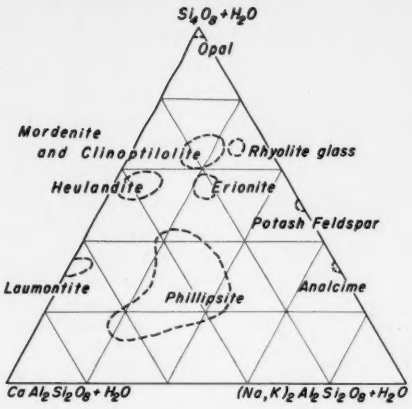

FIG. 2.—Compositional ranges of the mineral species mentioned in the text and the approximate composition of rhyolite glass, which is the material from which many of the authigenic zeolites are derived. The compositional variations of the zeolites are taken from Winchell (1937).

quite easily outside of its stability field, indicating that at surface temperatures the kinetics of nucleation and of crystal growth are important in determining the products formed from the alteration of vitric ash.

It was first suggested by Ross (1928) that zeolites could be formed by the action of saline lake water on clay minerals. Foster and Feicht (1946) reported a synthesis of analcime at 90° C and atmospheric pressure from the action of a strong NaOH solution on kaolinite. Although there is no direct proof that it is impossible to produce zeolites from clay minerals in natural environments, the frequent association of zeolites with volcanic materials indicates that volcanic fragments are the usual parent substance.

The experimental syntheses of zeolite minerals usually start with silica-alumina-alkali gels and the temperatures are higher than those which produced many natural zeolite occurrences. Since the natural process frequently starts with volcanic glass, the experimental work on the action of water on glass furnishes some useful data.

Hovestadt (1902) has compiled a summary of research on the reaction of water with a variety of laboratory and optical glasses and the following discussion is based on his conclusions.

The initial action of pure water is to exchange hydrogen ions from the water for sodium and potassium from the glass surface, making the water alkaline and increasing its capacity for dissolving silica. The possibility exists that under natural conditions the alkaline environment necessary for the production of zeolites can be produced by the hydrolysis of the glass after deposition, therefore the zeolites are not necessarily indicators of alkaline depositional environments. The rates of solution of ordinary commercial glass reported by Hovestadt (1902) range from 1 to 100 micrograms per 100 square centimeters per day, the rate being sensitive to temperature, glass composition, and water circulation. If natural glass shards of the size range encountered in most sediments reacted on their surfaces at these rates they would dissolve entirely in 30 to 3000 years. It is therefore likely that zeolites are produced during diagenesis not from an internal devitrification process but from the solution of material from the glass surface and the organization of that material into crystalline zeolites.

SUMMARY

Many sedimentary sequences contain volcanic material, and volcanic glass is particularly susceptible to alteration which may produce clay minerals, zeolites, or authigenic feldspars, and the mineralogy of the products promises to be a useful indicator of the conditions during diagenesis.

A better understanding of the significance of zeolites in sedimentary rocks can come from the following sources:

1) Laboratory studies of the conditions under which the various zeolite species form and studies of the mechanism of reactions between volcanic glass and sea and lake water.
2) Studies of modern sediments which emphasize the chemistry of the depositional and diagenetic environments as well as the nature of the source material.
3) Studies of the association of particular zeolite minerals with various sedimentary facies, along with attempts to reconstruct the chemical environment in which the rocks were formed.

REFERENCES

AMES, L. L., JR., SAND, L. B., AND GOLDICH, S. S., 1957, A contribution on the Hector, California bentonite deposit: Econ. Geology, v. 53, p. 22–37.

ARRHENIUS, GUSTAV AND GOLDBERG, E. D., 1955, Distribution of radioactivity in pelagic clays; Tellus, v. 7, p. 226–231.

AXELROD, D. I., 1950, Evolution of desert vegetation: Carnegie Inst. Washington Pub. 590, p. 215–306.

BALDWIN, J. L., 1944, Tupungato oil field, Mendoza, Argentina: Am. Assoc. Petroleum Geologists Bull., v. 28, p. 1455–1484.

BASKIN, YEHUDA, 1956, A study of authigenic feldspars: Jour. Geology, v. 64, p. 132–155.

BOLDYREVA, A. M., 1953, Authigenic analcime in Upper Permian sediments of the Chkalova and Aktyubinsk districts: Zapiski Vsesoyuz. Mineralog. Obshchestua, v. 82, p. 291–297. Chem. Abs. 48: 5030f.

BRADLEY, W. H. 1929, The occurrence and origin of analcite and meerschaum beds in the Green River Formation of Utah, Colorado, and Wyoming: U. S. Geol. Survey Prof. Paper 158-A.

BRAMLETTE, M. N. AND POSNJAK, E., 1933, Zeolite alteration of pyroclastics: Am. Mineralogist, v. 18, p. 167–171.

BUR'YANOVA, E. Z., 1954, Analcime sedimentary rocks from Tuva (S. Siberia): Doklady Akad. Nauk S. S. S. R., v. 98, p. 261–264. Chem. Abs. 49: 3751g.

——, 1956, Authigenic laumontite from Middle Devonian sandstone of Tuva: Vsesoyuz. Nauch.-Issledovatel. Geol. Inst. Information. Sbornik, No. 3, p. 77–79. Chem. Abs. 51: 13662c.

BUSHINSKY, G. I., 1950, Mordenite in Jurassic, Cretaceous, and Paleocene marine sediments: Doklady Akad. Nauk S.S.S.R., v. 73, p. 1271–1274. Chem. Abs. 45: 3768f.

CHASE, G. W., 1954, Permian conglomerate around Wichita Mountains, Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 38, p. 2028–2035.

COBBAN, W. A., 1955, Cretaceous rocks of northwestern Montana: Billings Geol. Soc. Guidebook, Sixth Annual Field Conference, p. 107–119.

COOMBS, D. S., 1950, The geology of the Northern Taringatura Hills, Southland: Royal Soc. New Zealand Trans., v. 78, p. 426–448.

———, 1952, Cell size, optical properties and chemical composition of laumontite and leonhardite, with a note on regional occurrences in New Zealand: Am. Mineralogist, v. 37, p. 812–830.

———, 1954, The nature and alteration of some Triassic sediments from Southland, New Zealand: Royal Soc. New Zealand Trans., v. 82, p. 65–109.

———, 1955, X-ray observations on wairakite and non-cubic analcime: Mineralog. Mag., v. 20, p. 699.

———, 1958, Zeolitized tuffs from the Kuttung Glacial Beds near Seaham, New South Wales: Australian Jour. Science, v. 21, p. 18–19.

CRAWFORD, A. L. AND COWLES, H. O., 1932, The Fuller's earth deposit near Aurora, Utah: Utah Acad. of Sci. Proc., v. 9 p. 55–60.

DEFFEYES, K. S., 1959, Erionite in Cenozoic tuffaceous sediments, central Nevada: Am. Mineralogist, v. 44, p. 501–509.

DANE, C. H., 1954, Stratigraphic and facies relationships of upper part of Green River Formation and lower part of Uinta Formation in Duchesne, Uintah, and Wasatch Counties, Utah: Am. Assoc. Petroleum Geologists Bull., v. 38,p. 405–425.

DZOTSENIDZE, G. S. SKHIRTLADZE, N. I., AND CHECHELASHVILI, I. D., 1956, Lithology and paleogeography of the Middle Jurassic coal-bearing deposits: Trudy Lab. Geol. Uglya, Akad. Nauk S.S.S.R., v. 5, p. 217–226. Chem. Abs. 51: 4229a.

ERMOLOVA, E. P., 1955, Analcime and mordenite in Oligocene and Miocene deposits of western Transcaucasia: Trans. Miner. Mus., Akad. Nauk, S.S.S.R., v. 7, p. 76–82. Mineralogical Abs. 31: 183.

ESKOLA, PENTTI, VUORISTO, URHO, AND RANKAMA, KALERVO, 1937, An experimental illustration of the spilite reaction: Comm. Geol. Finlande Bull., no. 119, p. 60–68.

FOSTER, W. D. AND FEICHT, F. L., 1946, Mineralogy of concretions from Pittsburgh coal seam, with special reference to analcite: Am. Mineralogist, v. 31, p. 357–364.

FYFE, W. S., TURNER, F. J., AND VERHOOGEN, J., 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. America Memoir 73.

GILBERT, C. M., 1951, Laumontite from Anchor Bay, Mendocino County, California: Geol. Soc. America Bull., v. 62, p. 1517.

——— AND MCANDREWS, M. G., 1948, Authigenic heulandite in sandstone, Santa Cruz County, California: Jour. Sedimentary Petrology, v. 18, p. 91–99.

HAYASHI, HISATO AND SUDO, TOSHIO, 1957, Zeolite-bearing bentonites: Mineralogical Journal, v. 2, p. 196–199.

HEY, M. H. AND BANNISTER, F. A., 1934, Studies on the zeolites: Part VII, "Clinoptilolite" a silica-rich variety of heulandite: Mineralog. Mag., v. 23, p. 556–559.

HOVESTADT, H., 1902, Jena glass and its scientific and industrial applications. (Translated by J. D. and A. Everett) Macmillan and Company, London, 419 p.

HUTTON, C. O., 1949, Occurrence of leonhardite: Geol. Soc. America Bull., v. 60, p. 1939–1940.

KALEY, M. E. AND HANSON, R. F., 1955, Laumontite and leonhardite cement in Miocene sandstone from a well in San Joaquin Valley, California: Am. Mineralogist, v. 40, p. 923–925.
KELLER, W. D., 1952, Analcime in the Popo Agie Member of the Chugwater Formation: Jour. Sedimentary Petrology, v. 22, p. 70–82.
———, 1953, Analcime in the Chinle Formation of Utah correlative with the Popo Agie of Wyoming: Jour. Sedimentary Petrology, v. 23, p. 10–12.
KERR, P. F., 1931, Bentonite from Ventura, California: Econ. Geology, v. 26, p. 153–168.
——— AND CAMERON, E. N., 1936, Fuller's earth of bentonitic origin from Tehachapi, California: Am. Mineralogist, v. 21, p. 230–237.
MAYES, J. W., 1947, A further study of the Tepee Creek Formation, Wichita Mountains, Oklahoma: Unpublished Master of Science thesis, University of Oklahoma.
MERRIT, C. A., 1958, Igneous geology of the Lake Altus area, Oklahoma: Oklahoma Geol. Survey, Bull. 76, p. 56–58.
——— AND HAM, W. E., 1941, Pre-Cambrian, zeolite-opal sediments in Wichita Mountains, Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 25, p. 287–299.
MOREY, G. W. AND INGERSON, EARL, 1937, The pneumatolitic alteration and synthesis of silicates: Econ. Geology, v. 32, p. 607–761.
MUMPTON, F. A., 1958, Clinoptilolite redefined: Geol. Soc. America Bull., v. 69, p. 1620.
MURRAY, J., AND RENARD, A. F., 1891, Deep sea deposits: Scientific results of the voyage of H.M.S. *Challenger*, 1873–1876, London, 525 p.
NOLL, W., 1936, Über die Bildungsbedingungen von Kaolin, Montmorillonit, Sericit, Pyrophyllit, und Analcim: Min. pet. Mitt., v. 48, p. 210–247.
RENGARTEN, N. V., 1940, Authigenic analcime in the Kazanian sandstones of the Kirov. Region: Zapiski Vserossus. Mineralog. Obshchestua, ser. 2, v. 69, p. 50–53.
———, 1945, A zeolite from the mordenite group in the Upper Cretaceous and Paleogene marine deposits of the eastern slope of the Urals: Doklady Akad. Nauk S.S.S.R., v. 48, p. 591–593.
———, 1950, Laumontite and analcime from Lower Jurassic deposits in northern Caucasus: Doklady Akad. Nauk S.S.S.R., v. 70, p. 485–488. Chem. Abs. 45: 8945d.
ROSS, C. S., 1928, Sedimentary analcite: Am. Mineralogist, v. 13, p. 195–197.
———, 1941, Sedimentary analcite: Am. Mineralogist, v. 26, p. 627–629.
ROZENDAL, ROGER, 1959, Analcime in lignite: South Dakota Acad. Sci. Proc., v. 35, p. 39–41.
SAND, L. B., ROY, RUSTUM, AND OSBORN, E. F., 1957, Stability relations of some minerals in the Na_2O-Al_2O_3-SiO_2-H_2O system: Econ. Geology, v. 52, p. 169–179.
Shannon, E. U., 1921, Massive laumontite from Montana: Am. Mineralogist, v. 6, p. 6–7.
STRINGHAM, BRONSON, 1952, Fields of formation of some common hydrothermal-alteration minerals: Econ. Geology, v. 47, p. 661–664.
TOURTELOT, H. A., 1946, Tertiary stratigraphy in the northeastern part of the Wind River Basin, Wyoming: U. S. Geol. Survey, Oil and Gas Invest. Prelim. Chart 22.
VAN HOUTEN, F. B., 1954, Geology of the Long Creek-Beaver Divide area, Fremont County, Wyoming: U. S. Geol. Survey, Oil and Gas Invest. Map OM 140.
——— AND OLSON, R. C., JR., 1957, Lithology of Upper Triassic Lockatong Argillite: Geol. Soc. America Bull., v. 68, p. 1808.
VASIL'EV, V. S., 1954, Mordenite in Mesozoic and Cenozoic sediments of the lower Volga Basin and western Kazakhstan: Doklady Akad. Nauk S.S.S.R., v. 95, p. 149–151. Chem. Abs. 48: 13560a.
———, KOBLIN, M. F., AND KRASNOVA, V. N., 1956, Zeolites in the Mesozoic and Cenozoic deposits of the Penza area: Doklady Akad. Nauk S.S.S.R., v. 111, p. 410–412.
WANLESS, H. R., 1922, Lithology of the White River sediments: Am. Philos. Soc. Proc., v. 61, p. 184–203.
WEEKS, A. D., LEVIN, B., AND BOWEN, R. J., 1958, Zeolitic alteration of tuffaceous sediments and its relation to uranium deposits in the Karnes County area, Texas: Geol. Soc. America Bull., v. 69, p. 1659.
WINCHELL, A. N., 1937, Further studies of the zeolites: Am. Mineralogist, v. 22, p. 85–96.

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FIGS. 1–2, DECEMBER, 1959

THE FORMATION OF CROSS-BEDDING BY A MEANDERING OR BRAIDED STREAM[1]

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ABSTRACT

It is suggested that much cross-bedding may be formed by a current flowing at right angles to the dip of the foreset laminae of the cross-bedded unit. The laminae thus represent successive positions of the depositing bank of a meandering stream. A similar origin has already been proposed for cross-bedding formed by migrating beach-gullies. Fabric analyses of cross-bedded gravel show that some units have apparently originated in this way, and published investigations of cross-bedding dip directions often show patterns that are consistent with a meander-bank origin. Much more detailed work is required before any definite pronouncement as to the extent of occurrence of this type of cross-bedding can be made.

INTRODUCTION

Cross-bedding in subaqueous sediments is basically so simple a structure that there is an unjustifiable temptation to ascribe a single simple origin to it. Sorby's original explanation of cross-bedding of all sizes as structures formed by deposition from heavily-laden currents that are forced to drop their load upon reaching still, open water, has dominated the minds of geologists ever since it was put forward (Sorby, 1852, 1859). Basing their work on this theory, several investigators have tried to correlate varieties of cross-bedding, other than that formed in ripples, with properties of the depositing current such as velocity, depth, and gradient (Illies, 1949; McKee, 1957; Nevin and Trainer, 1927). It would appear that too little attention has been paid to such work as that of Straaten (1951) and Thompson (1937), which demonstrates the formation of several types of cross-bedding in beaches, spits and bars.

MEANDER-BANK OR POINT-BAR CROSS-BEDDING

Suspicion of this generally accepted theory led the writer to examine another possibility which could account for the bulk of intermediate-size cross-bedding. To outline this it is necessary to discuss a specific type of cross-bedding. Consider, for example cross-bedding occurring in extensive tabular layers in sandstone, each layer truncating the laminae of the layer below. The accepted explanation requires that material be thrown down in a slope, often of very low angle, whose lower part is frequently concave upwards. Truncation of the tops of cross-bedded layers is usually assumed to indicate a period of erosion which must be followed by uniform subsidence so that the next layer can be spread evenly over the area before renewed erosion and subsidence occur. But the evenness and persistence of the layers argues against any such erratic conditions. Moreover, if such conditions did occur, one would expect the formation of many layers to be interrupted by premature subsidence, leaving an abandoned front to be buried by the next advancing layer. Cross-bedding formed at the leading edge of a migrating underwater dune would have a truncated top, but the very impermanence of the dune suggests that the required lateral persistence would not be present.

Now if we suppose the direction of the depositing current to be at right angles to the direction of dip of the cross-bedded laminae, these difficulties disappear. Cross-bedding of this type could be produced by deposition on the sides of a meandering stream, the shape of the cross-laminae representing the shape of the depositing side of the stream. The word stream is used in the broad sense and covers all water currents of limited horizontal extent. An aggrading estuarine or

[1] This investigation will form part of a Ph.D. thesis to be submitted to London University. Manuscript received June 15, 1959.

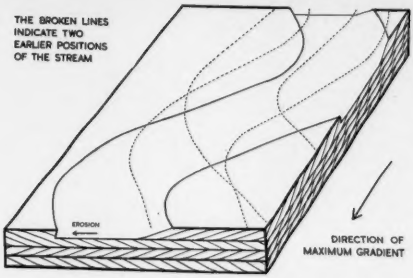

FIG. 1.—Diagrammatic illustration of the formation of cross-bedding by a meandering stream. Flat-bedded "flood-plain" deposits omitted.

river system with a complex network of meandering channels would be necessary for the production of an appreciable thickness of rock. Laminae of the underlying cross-bedded layer would be automatically truncated when the same channel swung back or the next channel moved across, unless there was a high rate of aggradation. Under conditions of no aggradation the previously formed layer would be completely removed and re-deposited. When, under aggrading conditions, a particular place was crossed by channels moving alternately to one side and the other "herringbone" cross-bedding would result. But since meanders migrate in the overall direction of stream flow as well as to and fro, there would be a preponderance of cross-laminae dips in one direction; superimposition of cross-bedded units apparently dipping in the same direction could be expected.

Figure 1 portrays this idea in its simplest form. The figure is only diagrammatic, and for the sake of simplicity the flat-bedded "flood-plain" deposits have been omitted since they will normally be removed by the undercutting stream. Their omission, and the unnatural evenness of the banks, give the impression that the depositing bank is at a higher level than the eroding one, but all this detail cannot be represented without unnecessarily complicating the drawing.

However, if it is possible for a stream to form an aggrading system when its only form of deposition is on the inside curves of meanders, then cross-bedding will be produced as indicated in figure 1, the extent of erosion of the layers depending upon the rate of aggradation. Lobeck (1939, p. 228) gives an illustration of the movement of meanders on the Mississippi above Natchez. His "channel bars" were apparently deposited at the inside curves of meanders, and as he states that these bars are truncated by the succeeding meander it is clear that cross-bedding of a comparatively simple type is being produced there at the present day.

Fisk (1947) makes a distinction between a meandering stream and a braided stream. Whereas a meandering stream deposits material principally on the inside curves of migrating meanders (meander bars, or point bars), a braided stream is so overloaded with sediment that lateral erosion is reduced and material is also deposited in the stream itself as channel bars. A braided stream is probably more likely to be an aggrading system than a meandering stream, but its deposits will not be so regular. This more complicated condition cannot easily be illustrated diagrammatically, but if it is granted that there can be an aggrading stream system in which all or most of the deposition is direct sedimentation from the stream, then it follows that the deposition will take place by the formation of channel bars and meander bars, as shown by observation of present-day streams; these bars will grow principally by lateral accretion of material on the channel banks, producing cross-bedded deposits which will be preserved by burial; the general dip of most of the cross-bedded laminae will be down the slope of deposition, though there will be several dips to the sides and a few reversals; and there will be truncation of cross-laminae by moving channels to a varying degree, dependent upon rate of aggradation.

EXPERIMENTAL WORK

In order to test the relationship between direction of current flow and direction of dip of cross-bedded laminae, the long-axis orientations of pebbles in 10 samples from cross-bedded units in gravel were measured. It was assumed that the long axes would be parallel to the direction of current flow, which is the generally accepted opinion (Pettijohn, 1957, p. 78). This was confirmed

TABLE 1.—*Details of samples collected for pebble-orientation measurements*

Sample	Locality	Weight of sample (lb) (about 120 pebbles)	Thickness of unit (ft)	True dip of foresets (degrees)	Nature of deposit	Angle between foreset dip direction and direction of maximum pebble frequency (degrees)
Callow Hill	6000 yd S65°E of Chertsey, Surrey	3	1½	22	sandy	60
Hertford A	4000 yd N25°E of Hertford	3¾	2	30	gravelly	40
Hertford B		¾	¾	20	sandy	80
Hertford C		5¼	1	25	very gravelly	60
Poynton A	1600 yd N80°E of Poynton church, Cheshire	2	2½	27	gravelly	20
Poynton C		2¼		27	gravelly	
Poynton D		3¼		24	gravelly	40
Poynton B		4	4	22	gravelly	60
Poynton E		3	1½	11	very gravelly	60
Whaley Bridge	1600 yd S70°W of Whaley Bridge station, Derbyshire	6½	25	20	gravelly	0

Poynton A, Poynton C and Poynton D were collected from different parts of one cross-bedded unit.

by the result from the Whaley Bridge sample mentioned below. Care was taken to ensure that the units chosen were not of the "festoon cross-lamination" type of Knight (1929). The method of collection and measurement was based on that described by Karlstrom (1952). Each sample comprised about 120 pebbles. The gravels were chosen for their abundant pebble content and undisturbed, unfolded disposition. Nine were Pleistocene and one, Callow Hill, was Tertiary (Bagshot); all came from well-exposed gravel-pits. Details of the samples are given in table 1. The total weight of the 120 pebbles in each sample is included to give an approximate indication of each sample's coarseness. The orientations were measured with respect to the perpendicular to the quarry face and plotted on histograms in 20-degree classes. Each class is combined with the class opposite it in the azimuthal circle; this keeps together pebbles that would otherwise be separated by small variations above or below horizontal. The histograms of three samples are shown in figure 2.

One sample showed preferred orientation of long axes down the slope of cross-bedding (with a secondary maximum at right angles, probably representing rolled pebbles). This came from a large unit where a downslope depositing current was to be expected. This result was useful in demonstrating that current direction would be reflected in the long-axis orientation of pebbles in these gravels. The maxima of the histograms prepared for the other samples show varying amounts of divergence from the direction of foreset dip. As far as can be judged from these few analyses, the degree of divergence is not related to depth of unit, dip of foresets, or coarseness of sample or deposit. However, as might be expected, the coarser deposits tend to give more confused histograms than do the finer; in addition to the turbulence set up by a gravelly stream floor, a deposited pebble will tend to be oriented as much by the configuration of such a surface of deposition as by the depositing current.

Apart from calling attention to the need for further research, the results show that in one of the examined units the depositing current was certainly at right angles to the dip of the foreset laminae; in four others it was probably at right angles; and in the remaining two units (Poynton A, C, and D being from one unit) a depositing current

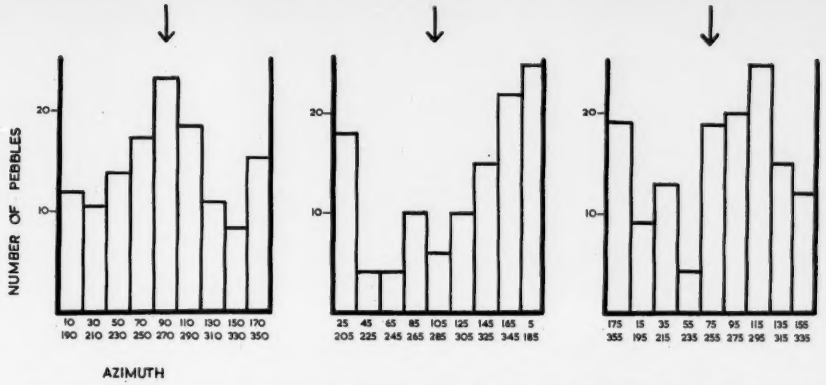

FIG. 2.—Histograms prepared from fabric analyses of Whaley Bridge (left), Hertford A (centre), and Hertford B (right) samples. Azimuth measured from normal to face of gravel-pit. The arrows indicate the direction of true dip of the foreset laminae.

running more or less in the direction of dip of the foresets is favored. Direct alignment of the pebbles with a depositing current at right angles to the dip of the foresets cannot be expected; there will always be some horizontal imbrication—pebbles will only come to rest if their upstream ends are protectively buried in the stream bank. This feature should allow actual direction of current flow, as distinct from line of flow, to be determined. However, other factors may be responsible for lack of direct alignment. Eddy currents may operate at the edge of the main current, or the material may be deposited at the ends of gravel bars.

EVIDENCE FROM THE LITERATURE

Cross-bedding dip directions are often used to determine the direction of sediment transport in a formation. These studies are based on many readings scattered throughout the formation. Several of these investigations have been reported in the literature, and many of these give results that could be explained by the origin suggested here. They show that cross-bedding dip directions are usually well spread through 120 or 180 degrees of compass direction, with a few dipping against the preponderance, though occasionally there are two dip maxima in opposing directions (Brett, 1955; Craig and others, 1955; Gilligan, 1920; McKee, 1940; Potter and Olson, 1954; Robson, 1956; Schwarzacher, 1953; Walker, 1955). It is not suggested that the meander-bank mode of origin of cross-bedding necessarily applies to each of these, but they are examples where that origin might be usefully considered. The pattern of cross-bedding dips may conceivably be affected by Coriolis Force, set up by the rotation of the earth, as it is known that the migration of meanders is affected in this way in some areas at the present day (Lobeck, 1939, p. 178).

Current directions determined for the same rock by cross-bedding and by other methods often show poor agreement. Rusnak (1957) found that current direction determined by cross-bedding dips differed by 60 degrees from that determined by grain orientation study. And although Brett (1955) found that current direction determined from ripples was in fair agreement with that determined from cross-bedding dips, Trow (quoted in Brett, 1955) found that there was sometimes no agreement.

Schwarzacher's observation that there is in general a positive correlation of median grain-size of Lower Cretaceous cross-bedding units with the thickness of those units can also be logically explained since both variables are likely to be dependent upon the size of the depositing stream (Schwarzacher, 1953).

As for observations on present-day sedimentation, Straaten (1954) has described deposition of material on the inside curves of migrating beach gullies in the Wadden Sea area, Holland. These gullies have been observed to move as much as 10 m in 120 days and leave behind cross-bedded deposits on the deposited bank. This process was earlier reported by Häntschel (1936); and recently Dunbar and Rodgers (1957) have suggested that some wide lenses of cross-stratified sediments may have been deposited as point bars on the inside curves of a meandering stream.

CONCLUSIONS

There is, therefore, ample evidence to show that while some cross-bedding can be produced by the mechanism first described by Sorby (1852, 1859), and in beaches, spits, and bars, it is possible that many varieties are produced by deposition at the edges of a braided or meandering stream. The scarcity of acknowledged purely fluviatile rock in the geological record may be due to misinterpretation of the environmental significance of cross-bedding. Too often the presence of cross-bedding gives rise to vague talk of "deltaic conditions," or "shallow seas." Full understanding of cross-bedding will only come with detailed study of the structure in old and recent deposits in its stratigraphic and petrographic context, bearing in mind the various possible origins. It is to ensure that the meander-bank or point-bar mode of origin will not be overlooked that this account has been written.

ACKNOWLEDGEMENT

I am indebted to Dr. W. E. Smith for reading the manuscript of this paper and making helpful suggestions.

REFERENCES

Brett, G. W., 1955, Crossbedding in the Baraboo quartzite of Wisconsin: Jour. Geology, v. 63, p. 143–148.

Craig, L. C. and Others, 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region, a preliminary report: U. S. Geol. Survey Bull. 1009E, p. 125–168.

Dunbar, C. O., and Rodgers, J., 1957, Principles of stratigraphy. John Wiley & Sons, Inc., New York 356 p.

Fisk, H. N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity. Waterways Expt. Station, Vicksburg, 82 p.

Gilligan, A., 1920, The petrography of the Millstone Grit of Yorkshire: Geol. Soc. London Quart. Jour., v. 75, p. 251–294.

Häntzschel, W., 1936, Die Schichtungsformen rezenter Flachmeer-Ablagerungen im Jade-Gebiet: Senckenbergiana, v. 18, p. 316–356.

Illies, Henning, 1949, Die Schragschichtung in fluviatilen und litoralen Sedimenten, ihre Ursachen, Messung, und Auswertung: Hamburg, Geol. Staatsinst., Mitt., v. 19, p. 89–109.

Karlstrom, T. N. V., 1952, Improved equipment and techniques for orientation studies of large particles in sediments: Jour. Geology, v. 60, p. 489–493.

Knight, S. H., 1929, The Fountain and Casper Formations of the Laramie Basin: Univ. Wyoming Publ. Sci., Geology, v. 1, p. 1–82.

Lobeck, A. K., 1939, Geomorphology: McGraw-Hill Book Co., Inc., New York, 731 p.

McKee, E. D., 1940, Three types of cross lamination in Paleozoic rocks of Northern Arizona: Am. Jour. Sci., v. 238, p. 811–824.

———, 1957, Flume experiments on the production of stratification and cross-stratification: Jour. Sedimentary Petrology, v. 27, p. 129–134.

Nevin, C. M., and Trainer, D. W., Jr., 1927, Laboratory study in delta-building: Geol. Soc. America Bull., v. 38, p. 451–458.

Pettijohn, F. J., 1957, Sedimentary rocks. 2nd. ed., Harper & Bros., New York, 718 p.

Potter, P. E., and Olson, J. S., 1954, Variance components of cross-bedding direction in some basal Pennsylvanian sandstones of the Eastern Interior Basin: Geological application: Jour. Geology, v. 62, p. 50–73.

Robson, D. A., 1956, A sedimentary study of the Fell Sandstones of the Coquet valley, Northumberland: Geol. Soc. London Quart. Jour., v. 112, p. 241–262.

Rusnak, G. A., 1957, A fabric and petrologic study of the Pleasantview Sandstone: Jour. Sedimentary Petrology, v. 27, p. 41–55.

Schwarzacher, W., 1953, Cross-bedding and grain size in the Lower Cretaceous sands of East Anglia: Geol. Mag., v. 90, p. 322–330.

SORBY, H. C., 1852, On the oscillation of the currents drifting the sandstone beds of the south-east of Northumberland, and on their general direction in the coal field in the neighbourhood of Edinburgh: Geol. Soc. Yorkshire Proc., v. 3, p. 232–240.

———, 1859, On the structure and origin of the millstone-grit in south Yorkshire: Geol. Soc. Yorkshire Proc., v. 3, p. 669–675.

STRAATEN, L. M. J. U. VAN, 1951, Texture and genesis of Dutch Wadden Sea sediments: Proc. 3rd Int. Congress Sedimentology Netherlands, 5–12, July, 1951, p. 225–255.

———, 1954, Sedimentology of Recent tidal flat deposits and the Psammites du Condroz (Devonian): Geol. en Mijnb. (Nw. Serie), jg. 16, p. 25–47.

THOMPSON, W. O., 1937, Original structures of beaches, bars, and dunes: Geol. Soc. America Bull., v. 48, p. 723–751.

WALKER, C. T., 1955, Current-bedding directions in sandstones of Lower *Reticuloceras* age in the Millstone Grit of Wharfedale, Yorkshire: Geol. Soc. Yorkshire Proc., v. 30, p. 115–132.

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FIGS. 1–3, DECEMBER, 1959

PISOLITES FORMED FROM THE OILFIELD WATER OF THE LULING FIELD, CALDWELL COUNTY, TEXAS[1]

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Seymour, Texas

ABSTRACT

Pisolites were being formed in 1936 during aeration of the water from the oil wells of the Luling Field, Caldwell County, Texas. The field is a faulted monocline. Production is from the Edwards (Comanchean Cretaceous). In the wells, the Edwards is porous and rotten with oil in its upper portion and water in its lower. The oil and water were produced together and separated in settling tanks. The water was hot, saline, carbonated, and saturated with hydrogen sulphide. This poisonous gas had to be removed before the water was discharged into stream floodwaters. It was removed by aeration. The well water was led through pipes several inches in diameter to the top of wooden towers some 12 ft high where it was discharged. Pisolites formed in the violently agitated pools on the floor below.

The pisolites ranged from 3 mm to 50 mm in diameter, and their shapes ranged from spherical to ovoid to irregular. Their centers were irregular and usually surrounded by many thin concentric crystalline layers of calcium carbonate, probably aragonite. A few years after 1936 the method of aeration was changed.

INTRODUCTION

In the summer of 1936 Mr. F. B. Plummer gave the writer some pisolites produced in the aeration of the water from the Luling Oil Field, Caldwell County, Texas. The writer later visited this field and obtained more pisolites as well as deposits from the drainage ditches.

In this paper a brief sketch of geological conditions in the Luling Field is given, based on the references cited (Brucks, 1929; Sellards, 1924). The causes and conditions of carbonate deposition have been so fully discussed, especially in very recent years, that only a short description of the pisolites and the way they formed will be given here. However, the method of aeration described here was changed in some details between 1936 and the early forties. For the newer method, see Plummer and Tapp (1943).

GEOLOGY OF THE LULING FIELD

The Luling Oil Field lies 4½ miles northwest of Luling, Texas. The structure is a faulted monocline (Brucks, 1929, p. 217) about 7 miles long and more than a half mile wide. It was the first important field to produce from the Edwards (Comanchean Cretaceous). Its first well was brought in in August, 1922. The surface rocks are Eocene; below them is the usual section of the Gulf Cretaceous. The Edwards is 1590–1720 ft below sea level in the producing wells; their altitude is approximately 600 ft. The Glenrose and Trinity lie below the Edwards, the Trinity resting on schists.

In the wells the Edwards is a rotted, very porous, dolomitic limestone, dark with oil, quite different from its resistant character in outcrops. The producing zone is in the upper part of the section; in the lower part the Edwards is partly cavernous and filled with water.

CHARACTER OF THE WATER

A great deal of water is produced along with the oil, all of it coming from the Edwards. The water is slightly more than 100°F and highly saline, the total solids being more than 13,000 ppm. (Plummer and Tapp, 1943, p. 147). Sodium chloride is the chief solute with considerable amounts of magnesium and calcium chlorides, calcium sulphate and bicarbonate, and traces of other substances (based on average analysis quoted by Plummer and Tapp, p. 147) also present. The water is saturated with hydrogen sulphide. At first this water was put into the San Marcos River, but the hydrogen sulphide in it killed the fish, so the water had to be aerated and kept in pools until floods in the river made it safe to release it. (J. G. Burr, Texas Fish and Game Commission, personal communication, 1936.)

FORMATION OF PISOLITES

After the oil-water emulsion had been separated in settling tanks, the water was

[1] Manuscript received June 24, 1959.

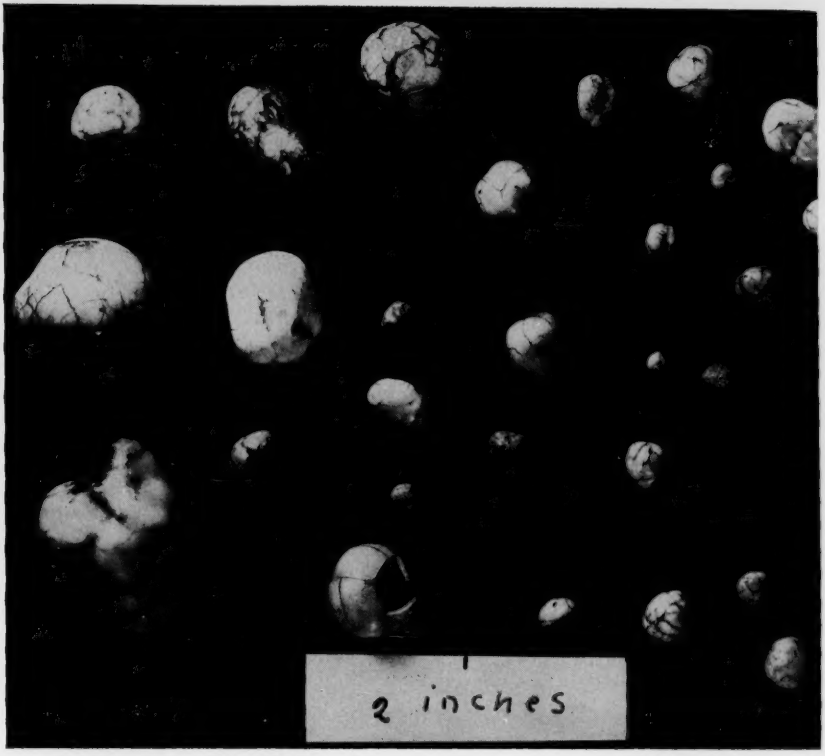

FIG. 1.—Shapes and sizes of pisolites formed from the water of the Luling oil field ×1.

led through pipes several inches in diameter to the tops of wooden towers approximately 12 ft high where it was discharged. The sides of the towers had planks across them only an inch or so apart. Stalactites and travertine formed on the sides. The pisolites formed in the shallow pools on the floors where the water was kept in violent agitation by the descending torrents. They could not be reached from the outside, but when the towers were torn down for cleaning, the pisolites could be recovered from the oily muck on the floors or from piles of it nearby.

Brightly colored sinter and travertine along with some free sulphur lined the drainage ditches leading from the towers.

DESCRIPTION OF THE PISOLITES

The pisolites range from 3 mm to 50 mm in diameter. Some pisolites are roughly spherical, some are ovoid, but many, especially the larger ones, are quite irregular in shape (fig. 1). Many of the larger pisolites have distinct radial cracks, especially in the outer layers. The centers are frequently non-crystalline masses containing a small amount of crude oil. Sometimes these centers seem to be a group of ooids, similar to those which form in the water from the hot springs at Thermopylis as it runs over a flat toward the Big Horn River. These ooids seem to have neither concentric or radial structure (writer's observations).

Sectioned Luling pisolites (figs. 2, 3) are distinctly concentric in structure with opaque layers often alternating with translucent ones. Some of the thicker layers are oily. As many as 35 to 40 rings were counted in a pisolite approximately 15 mm in diam-

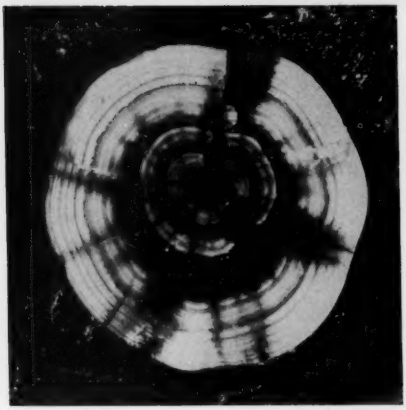

FIG. 2.—Section of spheroidal pisolite ×7.

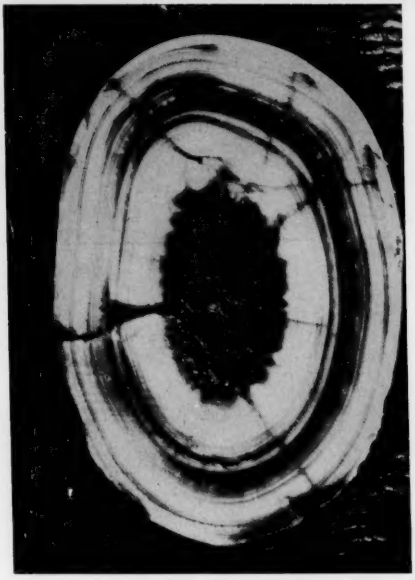

FIG. 3.—Section of ovoid pisolite ×5.

eter. The pisolites are almost completely soluble in hydrochloric acid. They contain traces of silicic acid and iron, a fair amount of aluminum, considerable magnesium, and a large amount of calcium, the last two as carbonates. (Qualtitative analysis by writer.) A spectroscopic analysis by Dr. Otto Watts (personal communication, 1936) showed no trace of barium or strontium.

Concentric structure (Twenhofel, 1932) p. 767 et seq.) is said to occur when the substances deposited are impure and radial when they are pure. No cases of radial structure were found in the pisolites sectioned.

Plummer and Tapp, (1943, p. 148) give the temperature of the oil-water emulsion as 106°F, and of water samples collected from various ditches as from 103 to 80°F so it seems likely that calcium carbonate was precipitated as aragonite (Twenhofel, 1932, p. 766, footnote 462; Revelle and Fairbridge, 1957, p. 255–274; Cloud and Barnes, 1957, p. 169–182). The presence of calcium sulphate in solution seems also to favor aragonite formation. However, Clark (1924, p. 205) states that calcite is much more common than aragonite in sinters. He does not discuss the possibility that some of the aragonite had already changed to calcite.

ACKNOWLEDGEMENTS

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REFERENCES

BRUCKS, E. W., 1929, The Luling oil field, Caldwell and Guadalupe counties, Texas: *in* Structure of typical American oil fields, v. 1, Am. Assoc. Petroleum Geologists, p. 256–281. Tulsa.

CLARK, F. W., 1924, The data of geochemistry, U. S. Geol. Survey Bull. 770. 841 p.

CLOUD, P. E., AND BARNES, V. E., 1957, Early Ordovician sea in central Texas: Geol. Soc. America Memoir 67, v. 2, p. 163–214.

PLUMMER, F. B., AND TAPP, P. F., 1943, Chemistry of Luling oil field water: Texas Acad. Sci. Proc. and Trans., v. 27, p. 146–162.

REVELLE, ROGER AND FAIRBRIDGE, RHODES, 1957, Carbonates and carbon-dioxide: Geol. Soc. America Memoir 67, v. 1, p. 239–395.

SELLARDS, E. H., 1924, The Luling oil field in Caldwell county, Texas: Am. Assoc. Petroleum Geologists Bull., v. 8, p. 775–788.

TWENHOFEL, W. H., 1932, Treatise on sedimentation. 2nd ed., Williams and Wilkins, Baltimore, 926 p.

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FIGS. 1–6, DECEMBER, 1959

NOTES

PARAGENESIS OF EOCENE AND CRETACEOUS SANDS OF WEST TENNESSEE[1]

ROBERT E. HERSHEY[2]

This study is based upon binocular examination of the mineral content of 10 sand samples collected in the Mississippi Embayment section of West Tennessee, from the Kentucky state line to the Mississippi state line. The samples represent an aggregate thickness of approximately 150 feet of material from the McNairy sand of Cretaceous age and sands of the Claiborne and Wilcox (?) groups of Eocene age.

These sands have undergone three recognizable complete cycles of erosion and deposition and are now in the fourth recognizable cycle. Other cycles may have occurred but could not be traced in the samples.

All the sands in the samples examined were exceedingly well sorted and had a sorting coefficient of approximately one. Histograms representing these sands are similar to those of known marine and dune sands. The individual quartz grains are mostly subangular to subrounded, but a few are well-rounded. The heavy minerals are all stable-type minerals such as ilmenite, rutile, monazite, and zircon. No magnetite was found as individual grains, only as inclusions.

The first stage of sedimentation started with the erosion of igneous rock. Minerals other than quartz and magnetite were probably present originally but could not be traced through the erosional cycles because they are not found as inclusions. After deposition of quartz and magnetite, silicification took place in the sediments and the quartz cement enveloped some of the angular to rounded magnetite grains (figs. 1 and 2).[3] An unusual internal structure is present in some of the quartz grains as bituminous inclusions projecting around some of the magnetite inclusions into the enveloping silica. These inclusions are mushroom-shaped "clouds" generally light-green in color. Another unusual internal structure is "bedding-plane" concentrations of minute magnetite grains within an individual quartz grain. Some of these planes of magnetite inclusions are at an angle to each other (fig. 3). The magnetite inclusions are not restricted to these planes; a few are scattered at random throughout the grain. The bituminous inclusions and "bedding-plane" concentrations of minute magnetite grains suggest the possibility of a gel type of silica cementation.

During the second recognizable stage the quartz with included magnetite from the first stage was subjected to erosion and rounding followed by resilicification. At this stage only the quartz and magnetite are traceable. No heavy minerals other than magnetite and rare pyrite or pyrrhotite were found as inclusions.

The third recognizable stage is shown by subangular quartz grains that contain as inclusions rounded quartz grains which in turn contain angular to rounded magnetite inclusions (fig. 4). As many as five individual rounded quartz grains are present in one subangular quartz grain. The quartz grains of the third stage are subangular, clear, and gently rounded on the edges. During this stage, or possibly later, other heavy minerals such as rutile, monazite, zircon, kyanite, garnet, spinel, tourmaline, topaz, ilmenite (including leucoxene) and others were introduced. More quartz grains and occasional grains of chert were added.

After the last deposition of the beds some mica was formed. The fact that mica was

[1] Manuscript received August 17, 1959.

[2] Principal Geologist, Tennessee Division of Geology, Nashville.

[3] All illustrations by Robert A. Miller, Geologist, Tennessee Division of Geology, Nashville.

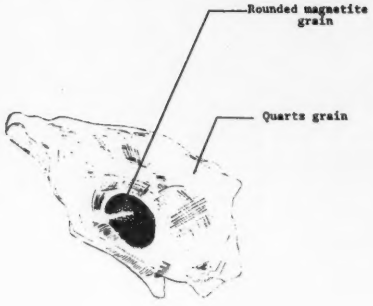

FIG. 1

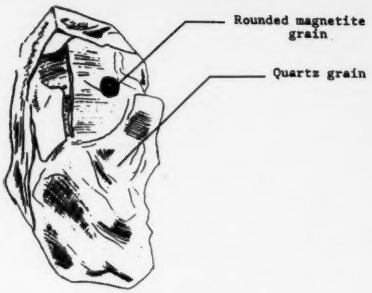

FIG. 2

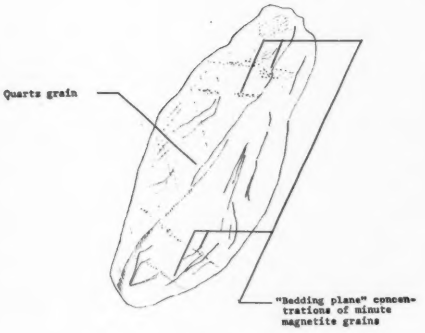

FIG. 3

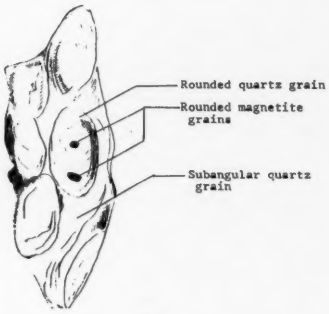

FIG. 4

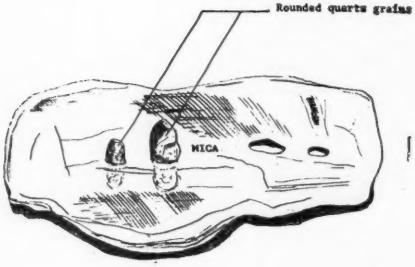

FIG. 5

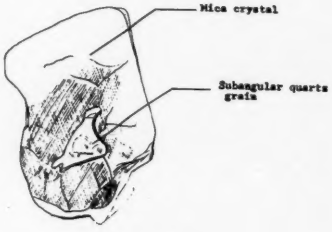

FIG. 6

formed after deposition is illustrated by rounded grains of quartz and weathered pyrite as inclusions in mica crystals (fig. 5; pyrite not shown). The subangular quartz grain in figure 6 is composed of two well rounded quartz grains cemented by silica. This subangular grain has gently rounded edges. Some mica crystals were distorted around quartz grains but are definitely later than the quartz grains. No shatter effects were present to indicate that the quartz grains were "pressed into" the mica. The extreme fragile nature of the mica would preclude much movement after formation and retention of the quartz inclusions. Some mica probably was present throughout the cycles of erosion and deposition, but some of the mica in the present formations is definitely postdepositional.

The clay in the present sand deposits is interstitial and probably was distributed throughout the sand by ground water. Iron oxide is now being introduced by ground water.

REMOVAL OF HEAVY LIQUID SEPARATES FROM GLASS CENTRIFUGE TUBES[1]

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Centrifuging a sample of sediment in a tube filled with bromoform or other heavy liquid is an excellent means of separating the heavy fraction of the sample from the light. Successfully removing the separated fractions presents a problem. Pouring off the liquid containing the lighter portion seldom results in a clean separation of the light and heavy minerals. Many of the grains that are being poured off adhere to the sides of the tube and may become mixed with the remaining fraction. A method which makes use of lucite tubes has been tried which involves freezing the liquid in the tubes following separation and cutting the tubes into two parts, one part containing the heavy minerals, one containing the light. The two sections were allowed to melt and the liquids in each were poured and filtered separately. This method was found to be time consuming and inefficient. Freezing of all the bromoform in the tubes required a long time and much of the bromoform was lost during the cutting process. In addition, the lucite tubes dissolved in acetone, a fact which made the complete removal of the grains adhering to the sides of the tubes almost impossible.

A method which the writer has used successfully many times proceeds as follows:

1. Centrifuge the sample in bromoform using glass centrifuge tubes, preferably those with a pinched or tapered bottom.
2. Remove the tube from the centrifuge and immerse the bottom end, the one containing the heavy fraction, in crushed dry ice and allow the liquid in only that part to freeze.
3. Remove from ice and pour off the light fraction and the unfrozen bromoform. Rinse the tube with acetone to completely remove the light fraction.
4. Allow frozen portion to melt and then pour it off. The above method is advantageous for the following reasons:

1. Bromoform is concerned in that most of it may be recovered pure rather than diluted with acetone.
2. The freezing of the small amount of bromoform necessary requires only a minimum of time because of the rather high freezing point of the liquid (6-7°C.)

The writer has used this method in many heavy mineral separations and has found it to be rapid, efficient, and accurate, especially when dealing with a large number of small samples.

[1] Manuscript received Dec. 11, 1959.

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ANNOUNCEMENTS

PALEONTOLOGICAL AND MINERALOGICAL ASPECTS OF POLAR WANDERING AND CONTINENTAL DRIFT—A SYMPOSIUM[1]

Society of Economic Paleontologists and Mineralogists
Atlantic City, April 25–26, 1960

In 1926 a symposium on continental drift was held in New York, with 14 participants. Only two of these men are now living. They have witnessed, within the last few years, the growth of a concept that played no part in the arguments 30 years ago. Studies of remanent magnetism in rocks of all continents have supplied a mass of data that suggest wide "wandering" of the magnetic poles. As these studies have progressed on opposite sides of the Atlantic, the "track" traced by the shifting polar position, as deduced from data in North America, is consistently farther west than the "track" mapped with European data. This, it is suggested, indicates that slow shifting of the earth's outer shell has been attended by continental separation responsible for at least a large part of the Atlantic basin. Thus advocates of continental drift point to the new evidence as establishing and amplifying their claim of slowly shifting landmasses.

Anyone who has complacent belief in permanence of land distribution in relation to the Earth's axis should visit the astonishing exhibits in South Africa that record widespread glaciation, during late Paleozoic time, in a continental area now within warm-temperate and tropical zones. This glaciation occurred at moderate and low altitudes, as shown by intertonguing of the tills with marine deposits. Similar evidence is well displayed in low-latitude areas of three other continents. Since some wide lands enjoyed temperate and tropical climates while those glaciations were in progress, we must give serious consideration to claims that continents have moved differentially, that the earth's crust has shifted bodily, or that these two types of movement have been combined, as now favored by students of remanent magnetism.

The mounting interest in outer space is not likely to divert attention of earth scientists from absorbing problems of our own planet. Group discussions like that planned for Atlantic City assess the status of our attack on basic puzzles of the earth's crust, and may play at least a small part in leading to the finding of critical keys.

CHESTER R. LONGWELL

[1] For previous announcements on this symposium, see issues of the *Journal* for December, 1958; March and September, 1959.

PRELIMINARY ANNOUNCEMENT OF ANNUAL MEETING AND FIELD TRIP

PERMIAN BASIN SECTION
Society of Economic Paleontologists and Mineralogists
Abilene, Texas, April 21, 22, & 23, 1960

The annual technical and business meetings of the Permian Basin Section, Society of Economic Paleontologists and Mineralogists, will be held Thursday, April 21, 1960, in Abilene, Texas. The General Chairman is Dr. John P. Brand, Texas Technological College, Lubbock, Texas.

A field conference to study the Pennsylvanian and lower Permian is planned for Friday and Saturday, April 22 and 23, 1960. The General Chairman is Mr. Thomas Hambleton, Texaco, Box 1270, Midland, Texas.

Details of both the technical program and the field conference will be announced at a future date.

CARL ULVOG, *President*
Permian Basin Section

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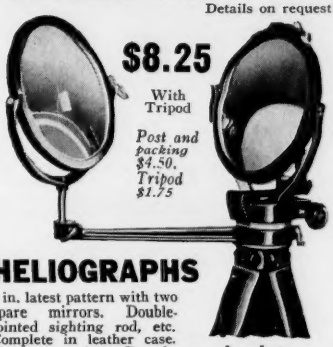

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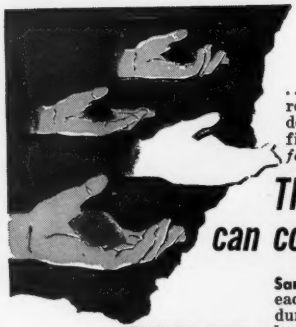

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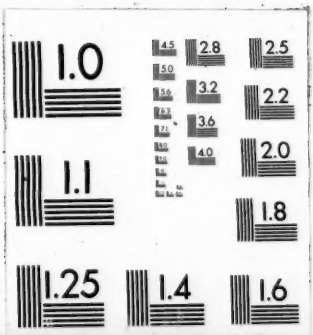
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